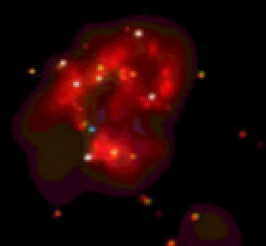
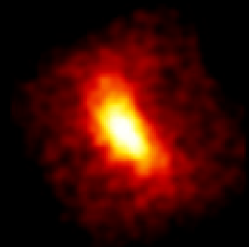
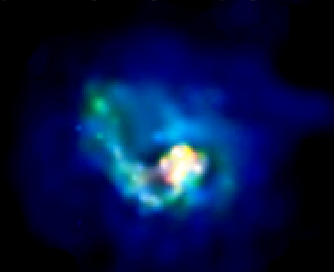
Constellation X

The Constellation X-ray Mission

SXT FMA Industry Study
Pre-Bidders Conference



November 5, 2003
GSFC Visitor's Center

Agenda

Section	Time	Topic	Presenter
	8:00	Registration/Coffee and Donuts	
1	8:30	Welcome and Introduction	Liz Citrin
2	9:00	FMA Procurement and SOW	Jean Grady
3	9:30	FMA and Technology Overview	Rob Petre
4	10:00	FMA Systems	William Podgorski
5	10:45	Optical Design	Timo Saha
6	11:15	Reflector Technology	Will Zhang
	11:45	Lunch — Served On-site	
7	12:30	Mechanical/Structural	Jeff Stewart
8	1:30	Grating Accommodation	Kathy Flanagan
9	2:15	Alignment and Metrology	Scott Owens
10	3:00	Reflector Metrology	Dave Content
11	3:15	Thermal Control	Mark Freeman
12	3:45	X-ray Test and Calibration	Jay Bookbinder
	4:15	Adjourn	

Constellation X
The Constellation X-ray Mission

Introduction

Elizabeth Citrin/GSFC
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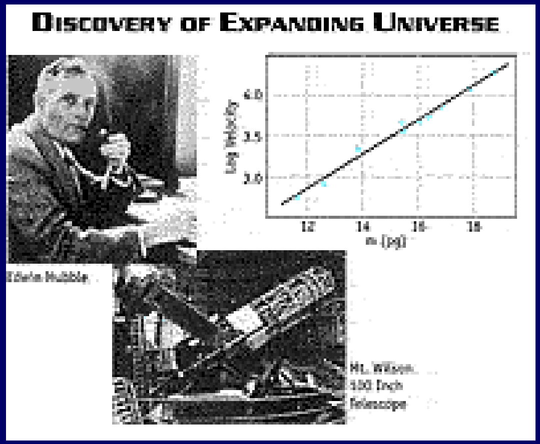
Einstein's Predictions

- **Three startling predictions of Einstein's relativity:**
  - The expansion of the Universe (from a big bang)
  - Black holes
  - Dark energy acting against the pull of gravity

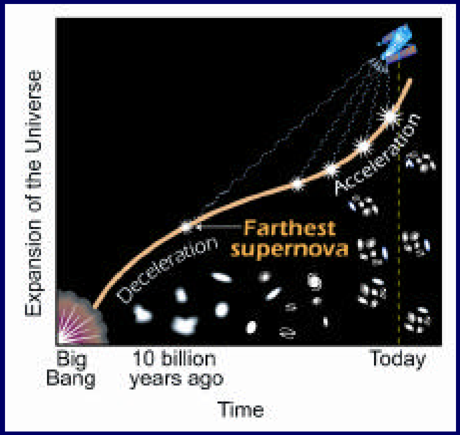
Observations confirm these predictions . . .

. . . the last only 5 years ago



Hubble discovered the expanding Universe in 1929

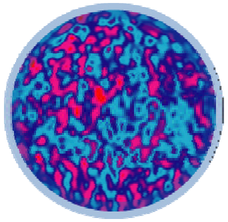
Black holes found in our Galaxy and at the center of quasars over the past three decades



Evidence for an accelerating Universe was observed in 1998

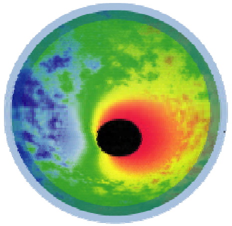
Completing Einstein's Legacy

Einstein's legacy is incomplete, his theory fails to explain the underlying physics of the very phenomena his work predicted



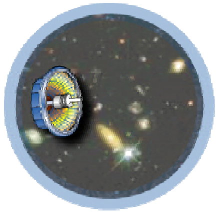
Big Bang

What powered the Big Bang?



Black Holes

What happens at the edge of a Black Hole?



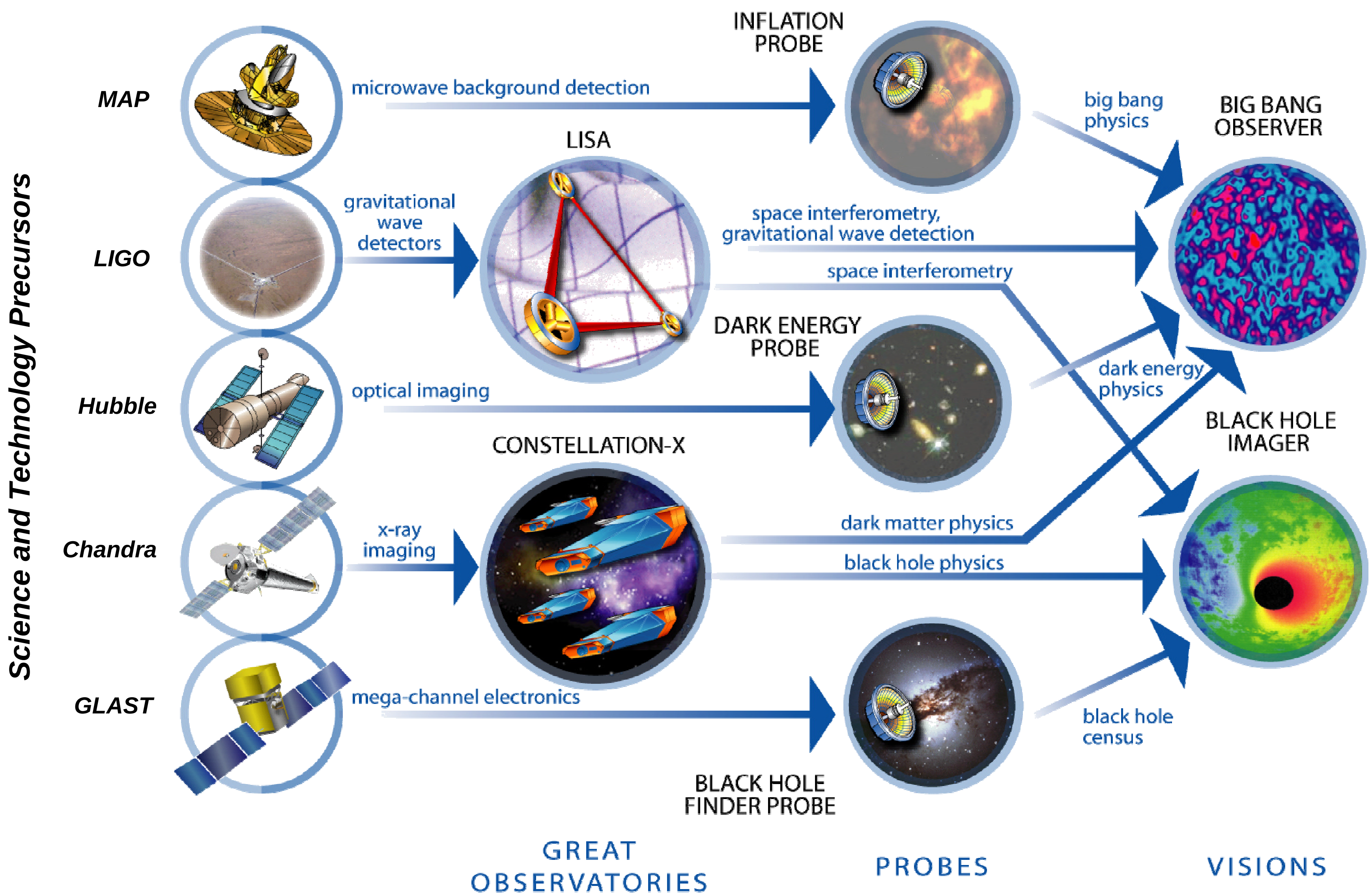
Dark Energy

What is the mysterious Dark Energy pulling the Universe apart?

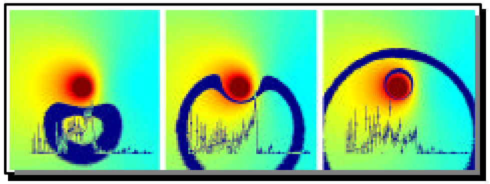
Beyond Einstein will employ a series of missions linked by powerful new technologies and common science goals to answer these questions …

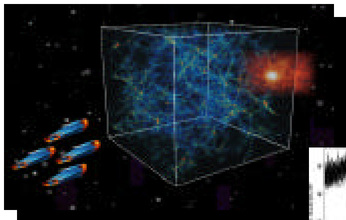
… and launch the revolution of the 21st century!

Beyond Einstein Program

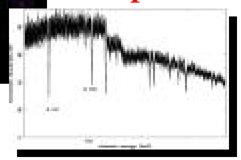


Constellation-X Key Features





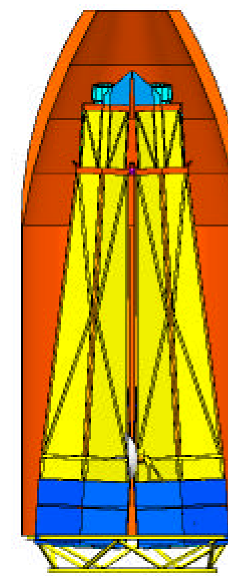
Absorption



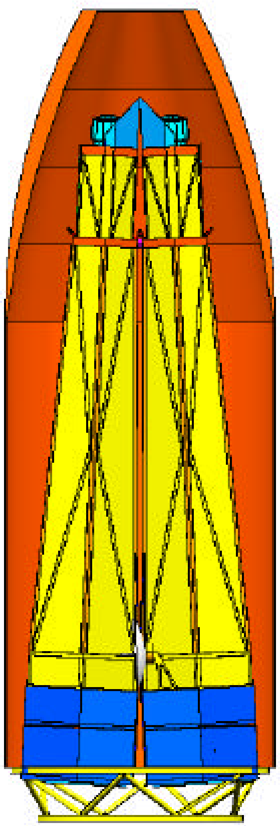
- **Large area X-ray Spectroscopy to Study:**
  - **Effects of strong gravity near supermassive black holes**
  - **Nature of dark matter and dark energy**
  - **Formation of supermassive black holes**
  - **Lifecycles of energy**

- **Mission Approach:**
  - **Four satellites launched two at a time on Atlas V class vehicle**
  - **L2 orbit for high efficiency, simultaneous observations**
  - **Modular spacecraft bus and telescope**

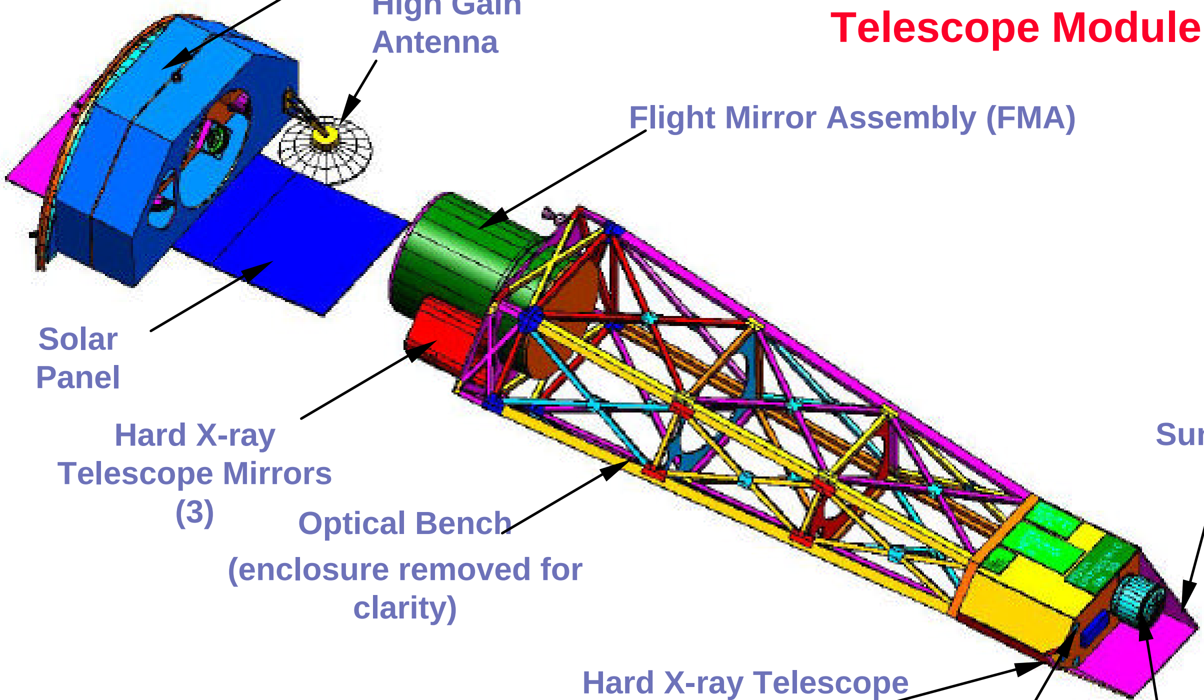
- **Schedule:**
  - **Launches in 2013 and 2014**
  - **Phase A starts in FY04**



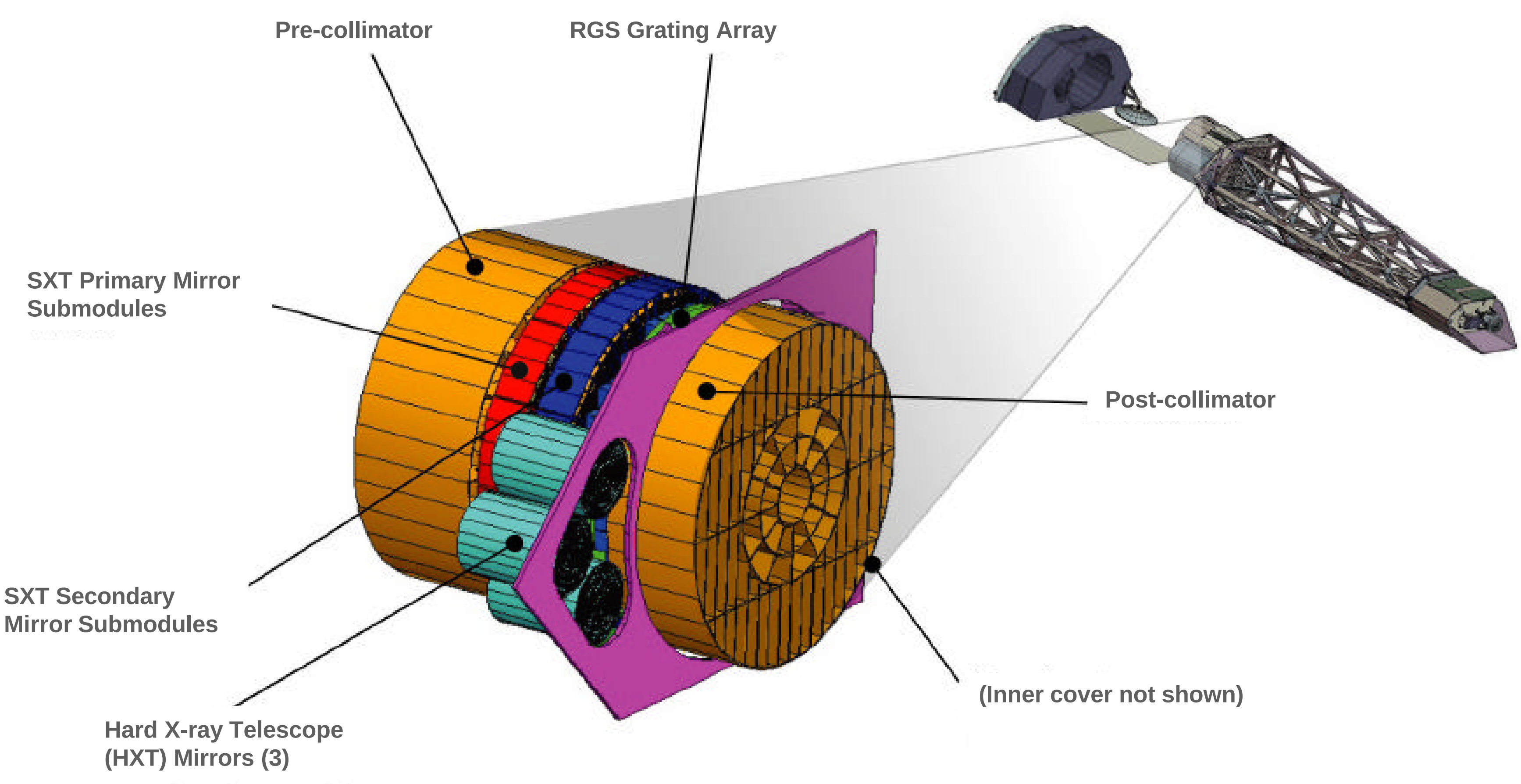
Mission Reference Configuration



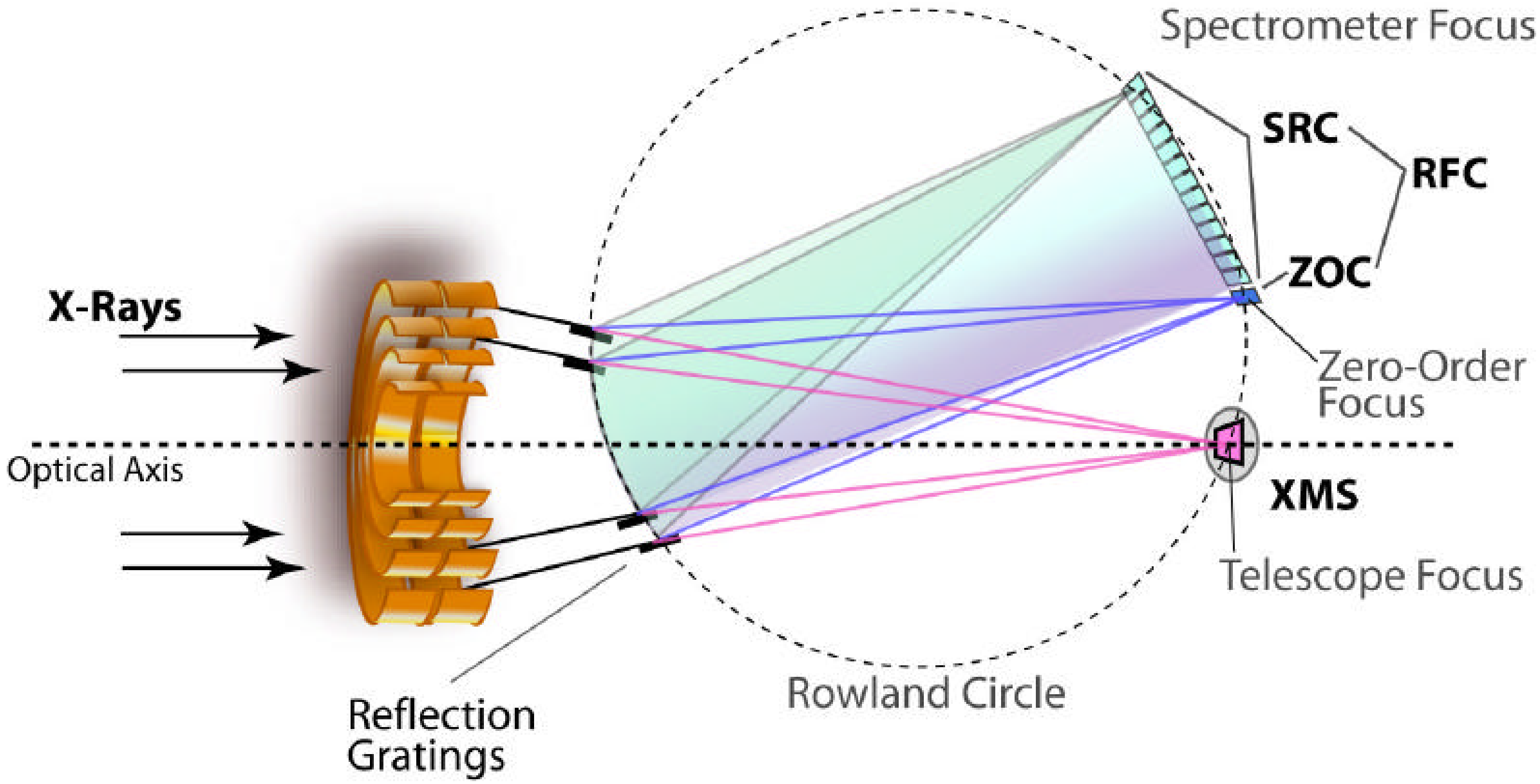
Launch Configuration



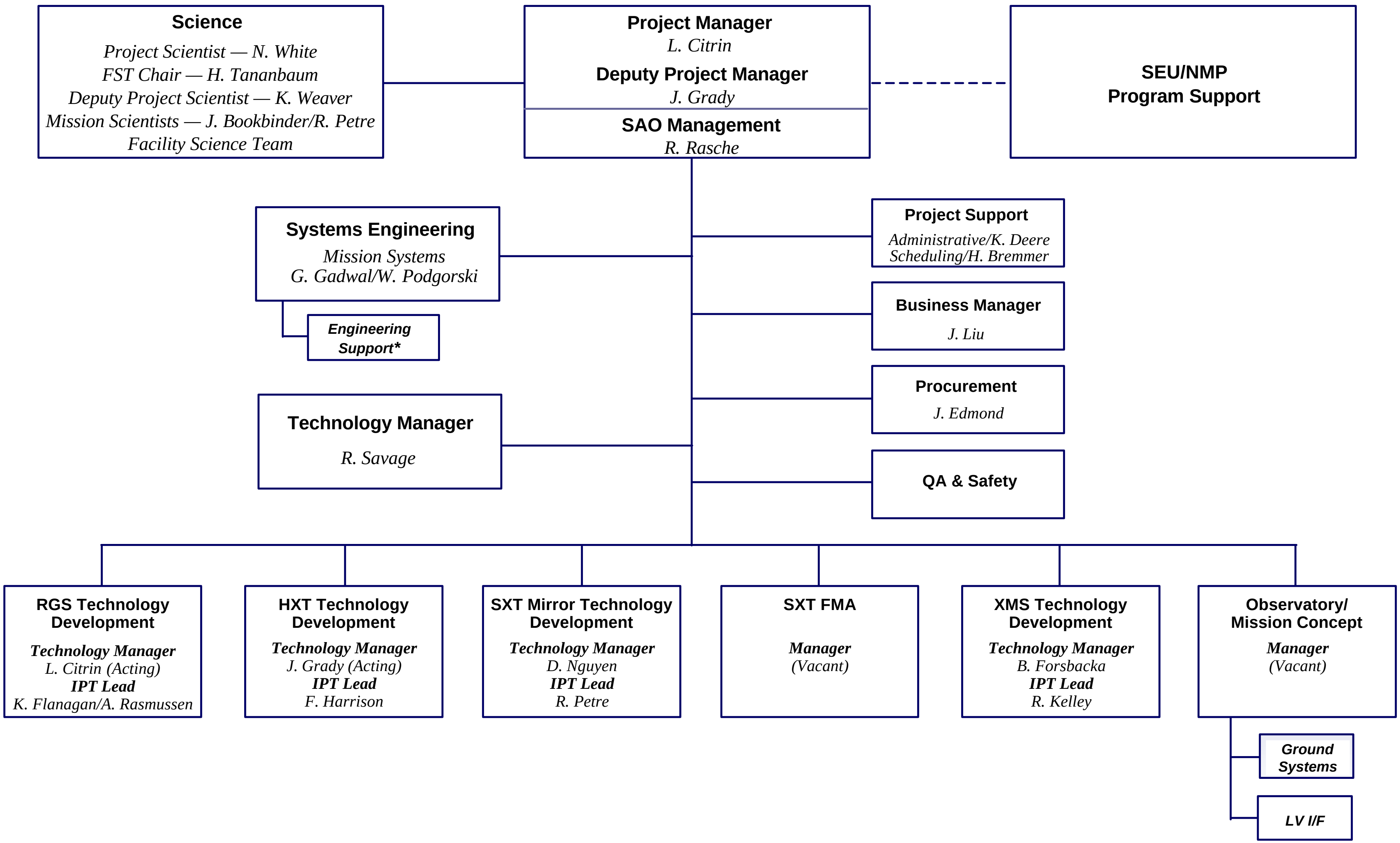
Constellation-X Observatory — Optics Module



SXT Optical Path



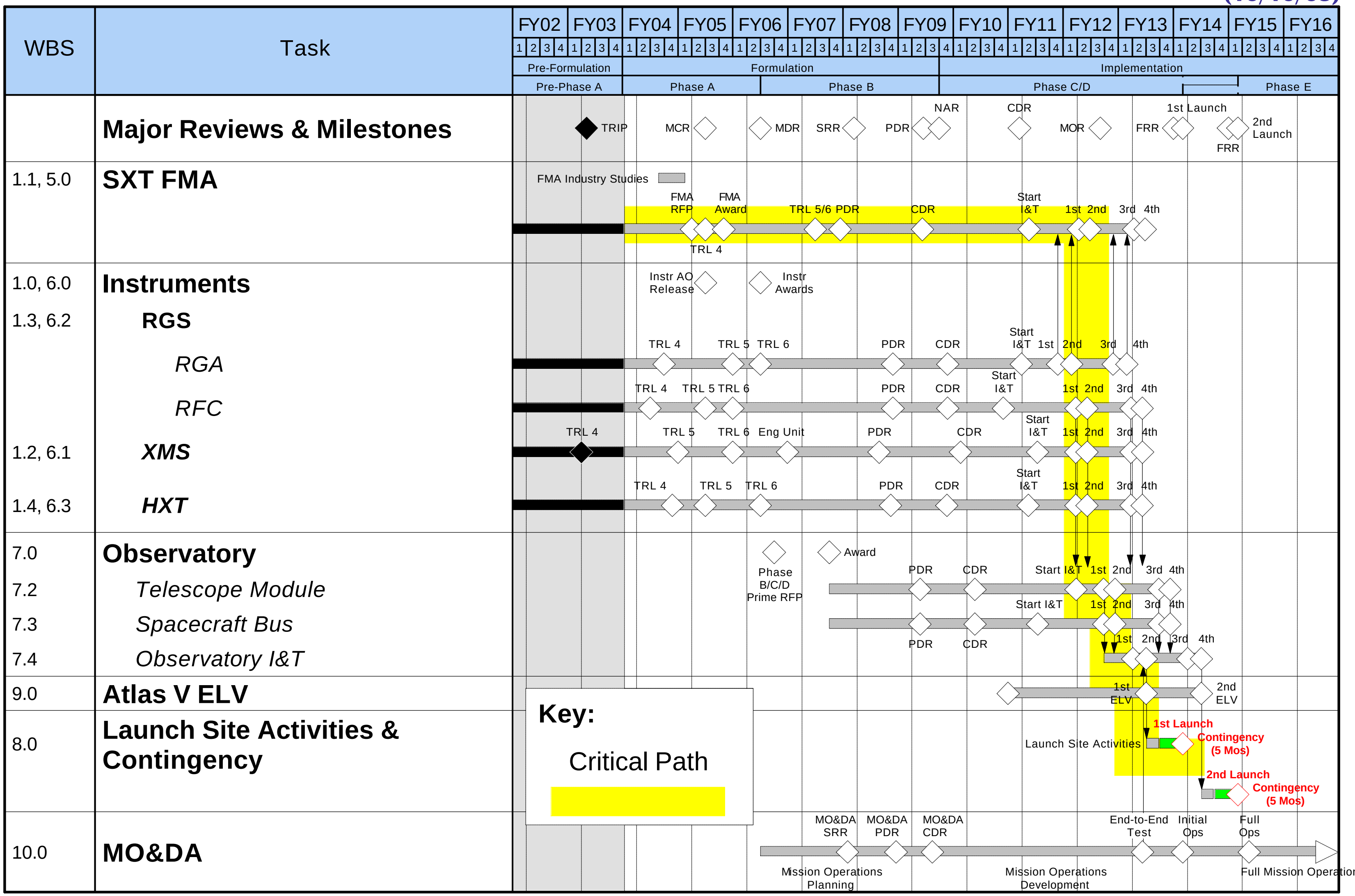
Constellation-X Formulation Organization



*Engineering Support: Mechanical, Thermal, Electrical, C&DH, Communications, Propulsion, Guidance, Navigation & Control, Flight Dynamics, Cryo-Systems

Mission Schedule

(10/10/03)



The Near Future

- The Beyond Einstein Initiative is here, but…
- The President’s budget has not been approved, but…
- We can anticipate various funding scenarios, and…

- The SXT FMA is the longest-lead most critical development element on Constellation-X
- Industry involvement in this element is a priority!

SXT FMA Industry Study Pre-Bidder's Conference — Nov. 5, 2003

Constellation X

The Constellation X-ray Mission

FMA Procurement Overview

Jean Grady/GSFC
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FMA Procurement Overview

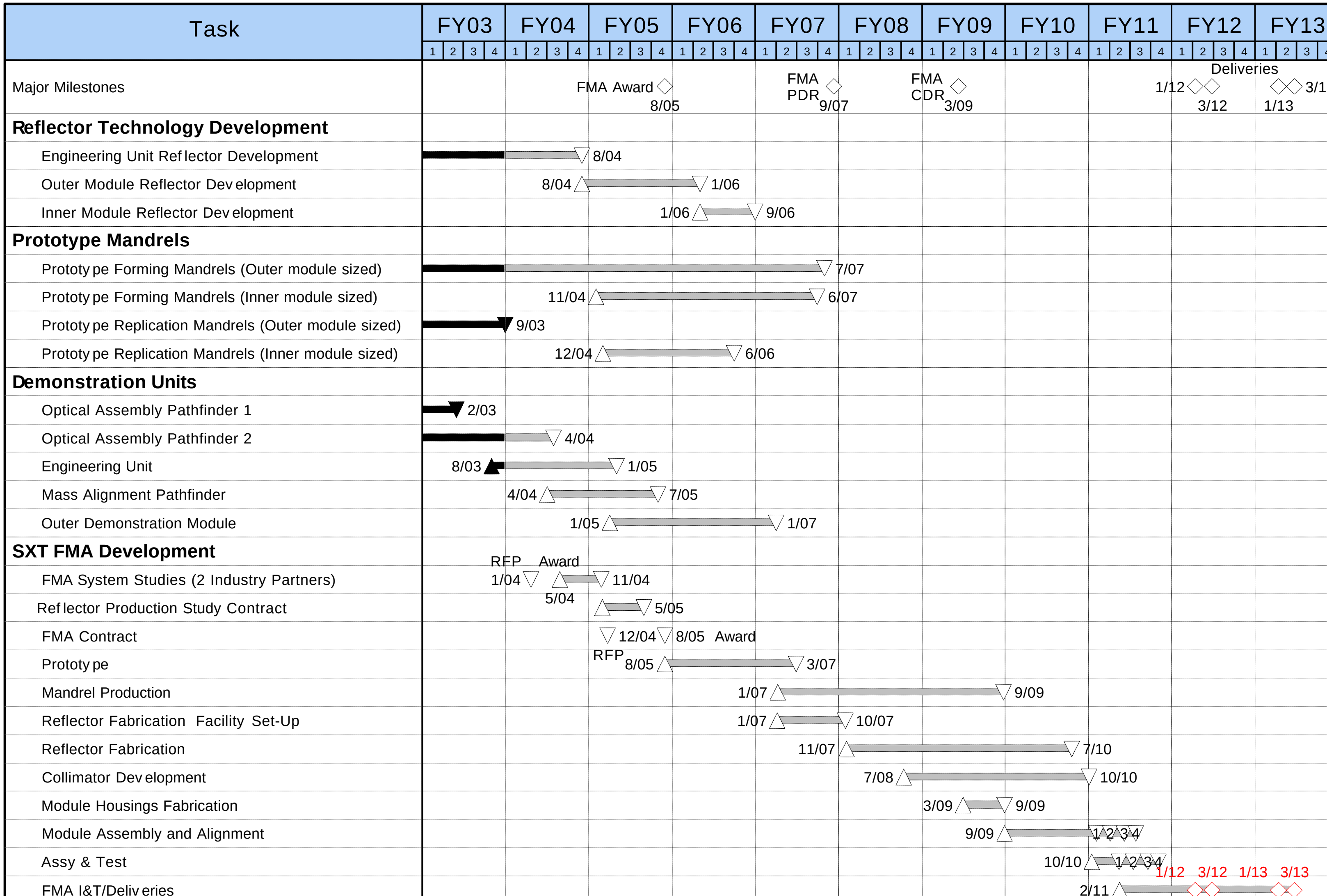
Topics

- FMA Acquisition Plans
- FMA Phase A System Study
  - Objectives
  - Overall Study Scope
  - Applicable Documents
  - Scope of FMA
  - Statement of Work
  - Schedule
- Summary

FMA Overall Acquisition

- SXT FMA is longest lead item for Constellation-X mission
- Phase A FMA study contracts starting Q3 FY04
  - FMA System Study (Multiple Awards ~ 6/04)
  - Reflector Production Study (Multiple Awards ~11/04)
- FMA contract award Q4 FY05 will include
  - Final prototype technology demonstration
    - Technology transfer
  - Four FMA's
    - Reflector production included
    - Mandrels may be GFE or included
    - Grating modules or assembly will be GFE (competed under Announcement of Opportunity)
- FMA deliveries to Observatory Q2 FY12 – Q3 FY13
  - FMA qualified and calibrated upon delivery

FMA Schedule



Objectives of FMA System Study Contract

- Begin FMA technology and systems knowledge transfer to potential industry FMA providers
- Develop an FMA design
- Provide input to and feed back on specifications at various levels
  - Technology development program specifications
  - Preliminary production specifications for Reflector Production Study contract
  - Reflection Grating Spectrometer interfaces
  - Observatory level specifications
- Develop strategies for FMA technology transfer
- Identify final stage(s) of FMA prototype
- Provide input in preparation for FMA flight procurement
  - Requirements and Interface definition
  - Cost and schedule ROM's

A Few Definitions.....

- Constellation-X mission Reference Configuration
  - Overview available in Constellation-X TRIP report
  - Includes observatory, launch and ground segment concepts
- FMA Reference Concept
  - Constellation-X Project FMA conceptual design
- Contractor FMA Study Design
  - FMA design developed by contractors under FMA Systems Study

Scope of FMA Systems Study

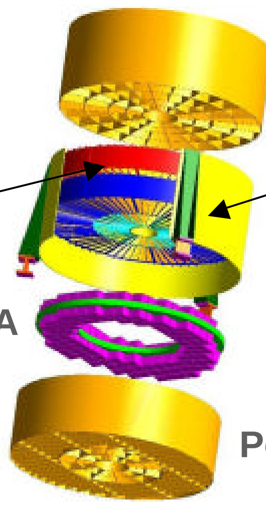
- Work included in this study
  - Assessment of FMA Reference Concept
  - Development of FMA Contractor Study Design
  - Development of Preliminary Flows for FMA Manufacturing, Integration and Test consistent with Contractor Study Design
  - Define FMA Prototype Unit consistent with Study Design
  - Development of Preliminary Cost and Schedules for Study Design
- Work not included in this study
  - Technology hardware development or demonstration
  - Study of mandrel production
  - Study of reflector production
  - Study or analysis relating to anything internal to grating modules such as grating alignment or mounting within modules

Applicable Documents

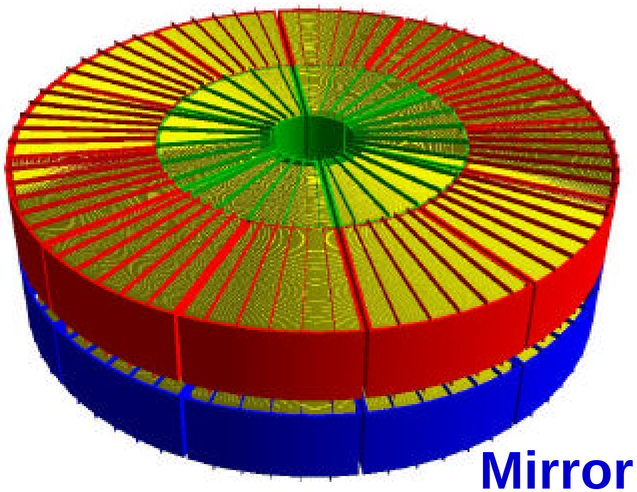
- Documents Applicable to SOW
  - FMA Requirements Document
  - FMA Reference Package
- FMA Reference Package
  - Describes FMA Reference Concept
  - Today's briefing provides basis
  - Defines reference papers and memos
  - Will be updated prior to RFP release
- FMA Requirements Document
  - Performance Requirements
  - Interface and implementation requirements
  - Grating module accommodation requirements
  - Reflector constraints
  - Programmatic assumptions
- Draft versions of SOW and FMA Requirements documents are available at:
  - https://conxproj.gsfc.nasa.gov/business/page.asp?base=business&target=businesspage

Scope of FMA for this Study

- "FMA" includes:
  - Mirror
  - Reflection Grating Spectrometer (RGS) Grating Array (RGA)
  - Collimators (Pre- and Post-)
  - Internal Cover
  - Supporting structure

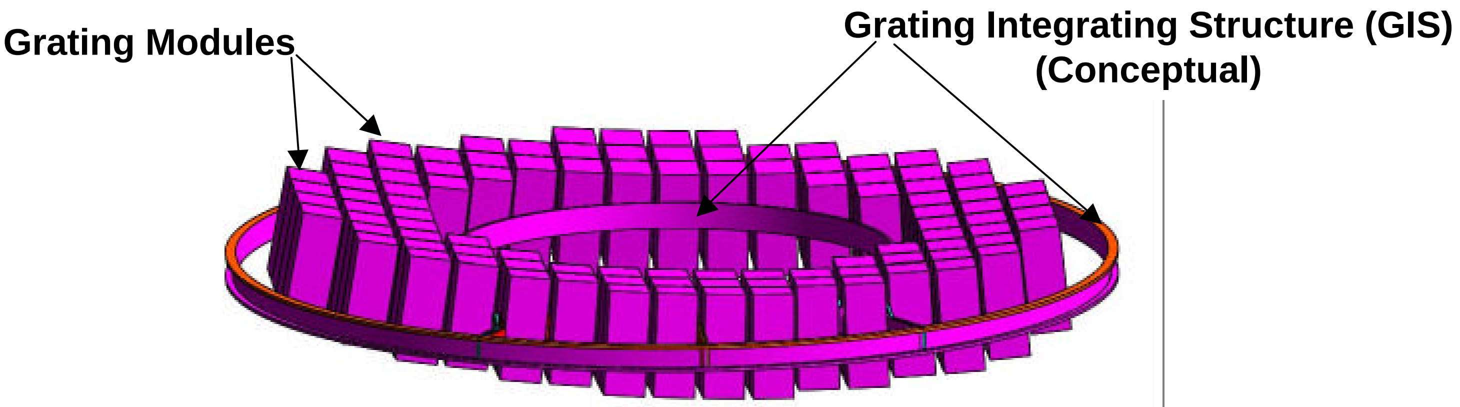


- "Mirror" includes:
  - Reflectors
    - Primary and Secondary
    - Properties Constrained under FMA Requirements Documents
  - Structural Support and Alignment for Reflectors



Scope of FMA for this Study (cont.)

- "RGA" includes:
  - Grating modules
    - Configuration and properties as defined in FMA Requirements Document must be used
  - Grating Integrating Structure (GIS)
    - GIS to be defined by contractor
    - GIS may be a separate structure or an integral part of the FMA



RGS Grating Array (RGA)

Task 1: FMA Reference Concept Assessment

- Assess Reference Concept
  - Technical and Programmatic risks
- Define approach for contractors study design including
  - Areas of the Reference that will be maintained (and further defined)
  - Areas that will be modified
- Results of Task 1 to be presented and discussed at Contract Kick-off meeting

Task 2: Generate Contractor FMA "Study Design"

- Emphasis on demonstration of ability to meet angular resolution (requirements and goal) and to maximize effective area
- Subtasks are highly iterative
- Important to address assembly, alignment, test, and calibration issues up front

Task 2: Generate Contractor FMA "Study Design" (cont.)

- Systems engineering
  - Performance Budgets
  - Requirement and goal for angular resolution
  - Requirements flow down
- Optical design and analyses
- Structural design and analyses
  - Reflector support
  - Mirror Modular design
  - Grating Integrating structure
  - Mirror and overall FMA structure
- Thermal design and analyses
  - Pre- and Post-collimators
- Provide Preliminary Plans for Manufacturing, Integration, and Test, and Calibration
  - Mirror module/subsystem assembly, alignment and test
  - FMA integration, alignment, and verification testing
  - Includes all four FMA's

SOW Tasks 3 – 5

- **Task 3: Reflector Parameter Sensitivity Trade**
- **Task 4: Define Prototype Unit which, when built and tested, will**
  - Verify the important aspects of the total FMA design
  - Demonstrate Technology Readiness Level 6
- **Task 5: Provide Assessment of FMA Requirements Document**

SOW Task 6 – 8

- Task 6: Programmatic Summary
  - FMA development Schedule and ROM cost for 4 units (Reflector and Mandrel cost excluded)
  - Technical and programmatic risk assessment of contractors preferred design through all phases of program
  - Identification of facilities and special equipment
  - Suggestions for technology transfer approach
  - Delineation of assumptions used by contractor for study
- Task 7: Reviews
- Task 8: Final Report

Nominal Schedule for FMA Study Schedule

- Preparations and Procurement Activities
  - November 5, 2003 – Pre-bidders Conference
  - November and December 2003 – Site visits
  - Late December 2003 – Draft RFP release
  - January 2004 – RFP release
  - March 2004 - Proposals due
  - June 2004 – Study Contract Award
- Study
  - CSD + 3 weeks – Kick-off meeting
  - CSD + 2 months – Status review
  - CSD + 4 months – Status review
  - CSD + 6 months – Final review and final report

Summary

- Draft documents for FMA Systems Study have been generated and are available for review
- SOW
- FMA Requirements
- Today's presentation will summarize the FMA Reference Concept

We are looking for feedback on these as we prepare final solicitation

SXT FMA Industry Study Pre-Bidder's Conference — Nov. 5, 2003

Constellation X

The Constellation X-ray Mission

FMA and Technology Overview

Dr. Robert Petre/GSFC
SXT Mirror IPT Lead
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Outline

- Top Level Mission Requirements and Flowdown to FMA
- FMA Reference Concept
- SXT FMA Technology Development Roadmap
- Study Variables

Constellation-X Mission Requirements Flow Down

Science Goals

- Effects of Strong Gravity near Supermassive Black Holes
- Nature of Dark Matter and Dark Energy
- Formation of Supermassive Black Holes
- Lifecycles of Energy

Measurement Capabilities

Effective area:
15,000 cm^2 at 1.25 keV
6,000 cm^2 at 6.0 keV
1,500 cm^2 at 40 keV
1,000 cm^2 (0.25 to 10 keV)

Band pass:
0.25 to 40 keV

Spectral resolving power (E/DE):
≥ 300 from 0.25 to 6.0 keV
≥ 3000 at 6 keV
≥ 10 at 40 keV

System angular resolution and FOV:
15 arc sec HPD and
FOV > 5 arcmin dia (0.25 to 10 keV)

1 arc min HPD and
FOV > 8 arcmin dia (10 to 40 keV)

Engineering Implications

Effective area:
- Light weight, highly nested, large diameter (~1.6 m) mirror
- Long focal length (~10 m)

Band pass:
- 2 types of telescopes to cover energy range

Spectral resolving power:
- Dispersive *and* non-
- dispersive capability to cover energy band

System angular resolution and FOV:
- Tight tolerances on telescope figure, surface finish, alignment
- ≥ 30 x 30 array for x-ray calorimeter (pixels ~5 arcsec)
- Cryocooler driven by array size and readout electronics

Key Technologies

High throughput optics:
- High performance replicated segmented reflectors
- High reflectance coatings
- High strength, low mass materials for optical surfaces

High energy band:
- Multilayer optics
- CdZnTe detectors

High spectral resolution:
- 2 eV calorimeter arrays
- Coolers
- Lightweight gratings
- CCD arrays extending to 0.25 keV

Optical bench:
- Stable (time and temp.)
- High strength/low weight materials

Mission Performance Requirements

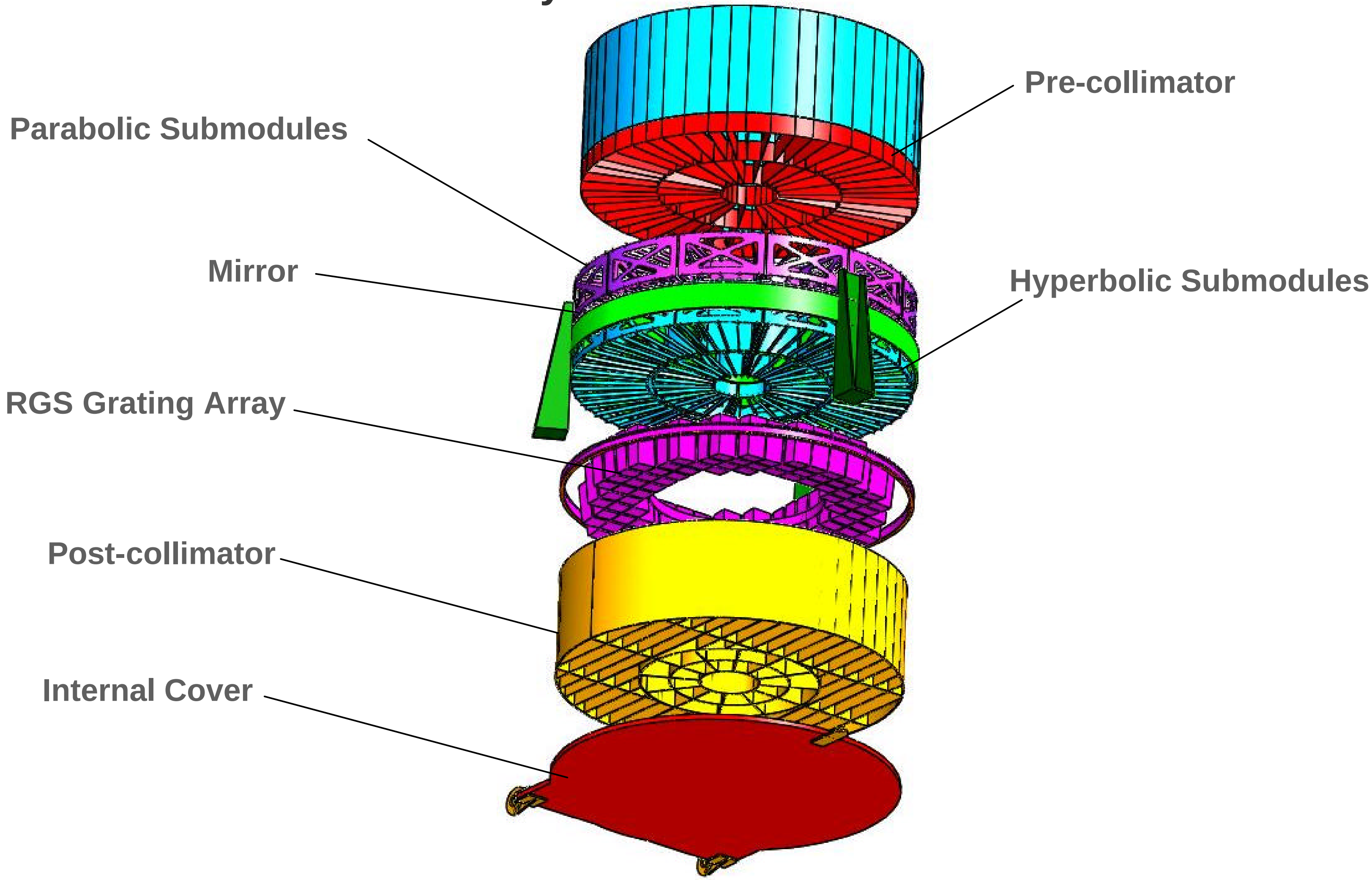
- **Mission science performance requirements:**
  - Mission level effective areas from 0.25 to 10 keV
    - Based on instantaneous observing requirements for time dependent phenomena
  - Angular resolution
    - Direct requirement based on confusion limit
    - RGA requirement for spectral resolving power has an implicit requirement on SXT mirror
    - These coincidentally result in 12.5 arcsec each for FMA
  - Mission level field of view (FOV)
    - Limited in practice by the detectors, not the optics
    - But places limits on FMA optical path internal alignments

FMA Performance Requirements and Goals

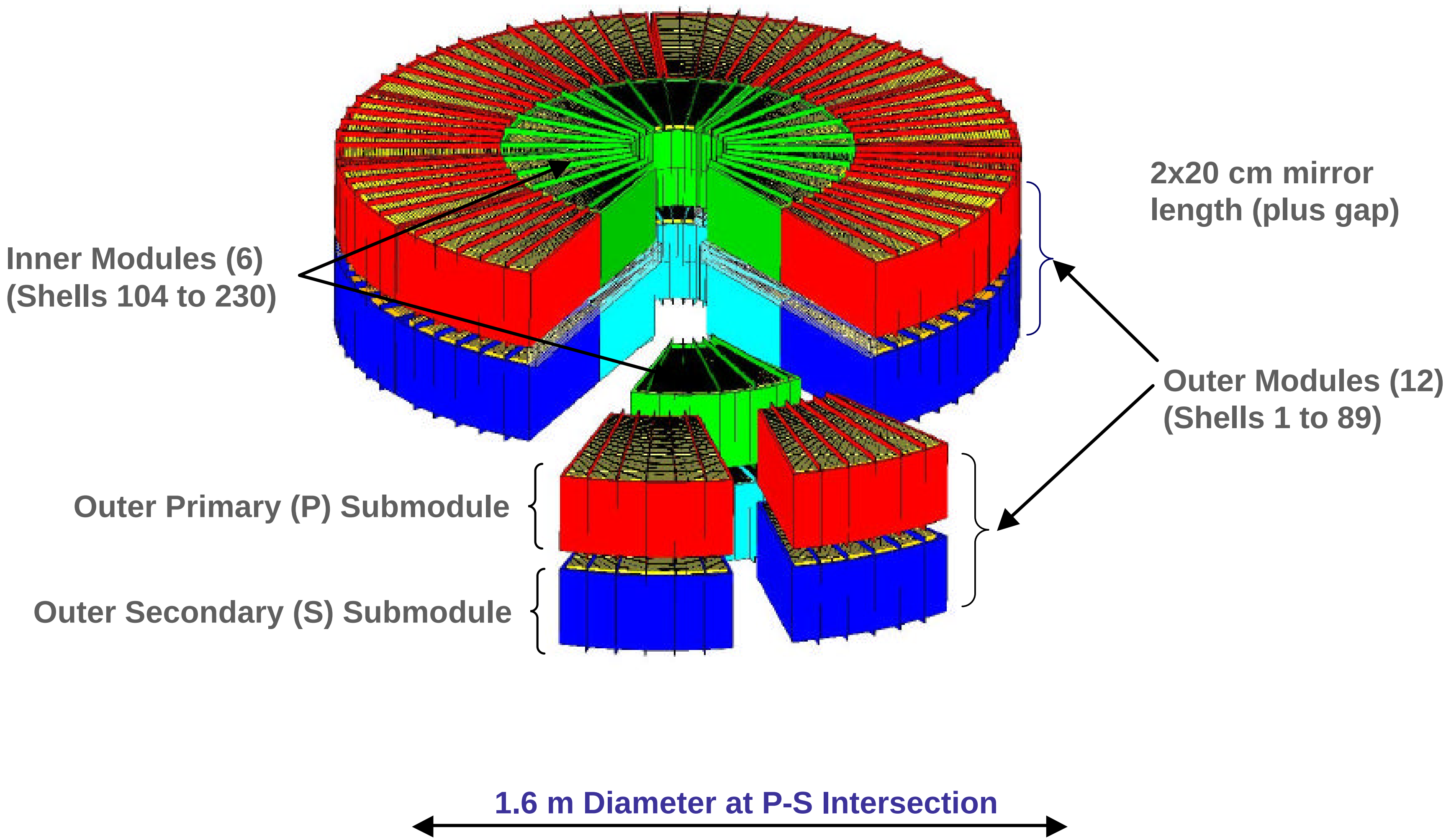
- Derived from top level science requirements
- FMA effective area
  - 9630 cm^2 at 0.25 keV
  - 7250 cm^2 at 1.25 keV
  - 1730 cm^2 at 6 keV
  - 380 cm^2 at 10 keV
- FMA on-axis angular resolution on-orbit
  - Requirement: 12.5 arcsec Half Power Diameter (HPD)
  - Goal: 4 arcsec HPD
  - Study shall meet requirement, approach goal as closely as possible
- FMA field of view
  - Effective area at 2.5 arcmin off axis is >95 percent of on-axis effective area (at 1.25 keV)

SXT Flight Mirror Assembly (FMA) Reference Concept

- **1.6M Diameter FMA Assembly**



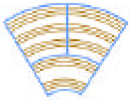
FMA Reference Concept Mirror Incorporates Modular Approach



FMA Reference Concept Mirror Design Parameters

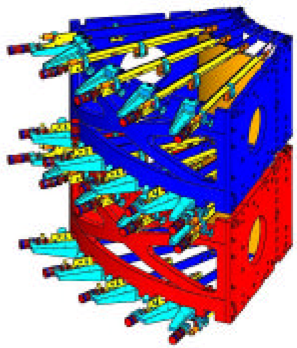
Parameter	Description
Design	Segmented Wolter I
Reflector substrate material	Thermally formed glass
Reflecting surface fabrication	Epoxy replication
X-ray reflecting surface	Gold
Number of nested shells	127 (inner); 89 (outer)
Total number of reflectors	3660
Reflector length	20 cm
Number of modules	6 (inner); 12 (outer)
Module housing composition	Titanium alloy, CTE-matched to substrate
Largest reflector surface area	0.08 m^2
Reflector substrate density	2.4 gm/cm^3
Reflector thickness	0.41 mm
Reflector microroughness	0.4 nm RMS
FMA mechanical envelope	1.68 m dia x 1.98 m

Segmented X-ray Mirror Development Process

	Optical Assembly Pathfinder		Engineering Unit	Mass Production Pathfinder	Prototype Pathfinder	Prototype
	OAP #1	OAP #2				
Configuration						 Industry Development
Module Type	Inner	Inner	Inner	Inner	Outer	Sector (2 Outer & 1 Inner)
Housing Material	**Aluminum**	**Titanium**	Titanium/composite	Titanium/composite	Titanium/composite	Titanium/composite
Focal Length	8.4 m	8.4 m	8.4 m	8.4 m	10.0 m	10.0 m
Reflector Length (P&S)	2 x 20 cm	2 x 20 cm	2 x 20 cm	2 x 20 cm	2 x 20-30 cm	2 x 20-30 cm
Nominal Reflector Diameter(s)	50 cm	50 cm	50 cm±	50 cm±	160 cm± 120 cm± 100 cm	160 cm± 120 cm± 100 cm± 80cm±, 30 cm±
Goals	▪ Align 1 reflector pair (P&H) ▪ Evaluate mirror assembly design, alignment and metrology	▪ Align 1 reflector pair ▪ Evaluate reflector ▪ Evaluate mirror bonding ▪ X-ray test	Requirements: ▪ Align one reflector pair to achieve <12.5 arcsec ▪ X-ray test, vibration test (Q4 of FY04) Goals (Q2 of FY05): ▪ Replicate 3 mirror pairs using a single replication mandrel ▪ Align up to 3 reflector pairs to achieve <12.5 arcsec ▪ Environmental test	▪ Align 3 reflector pairs ▪ Evaluate tooling and alignment techniques for mass production ▪ X-ray test	▪ Flight-like configuration outer module ▪ Environmental and X-ray test ▪ Largest reflectors	▪ Demonstrate largest and smallest diameter reflectors ▪ Demonstrate module to module alignment ▪ Environmental and X-ray test
TRL	TRL 3		TRL 4		TRL 5/6	TRL 6
Timeframe	Q2 of FY03	Q3 of FY04	Q2 of FY05	Q4 of FY05	Q2 of FY07	Q3 of FY07
Technology Gate			◆		◆	

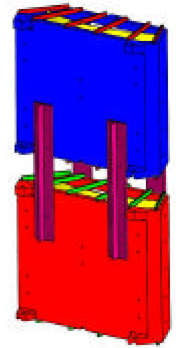
SXT Mirror Phased Technology Development

OAP 1



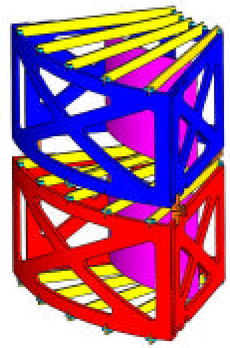
Inner Module (P&S)
Objective: Evaluate mirror assy design, alignment and metrology

OAP 2



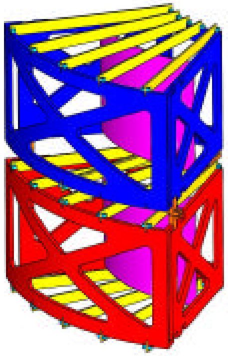
Inner Module (P&S)
Objective: Evaluate reflector, mirror bonding

Engineering Unit (EU)



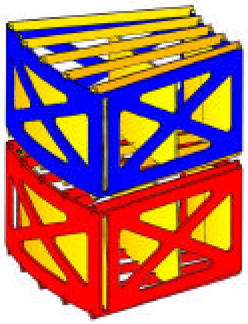
Inner Module (P&S)
Objective: Evaluate assembly gravity sag, titanium housing, X-ray and environmental test

Mass Alignment Pathfinder



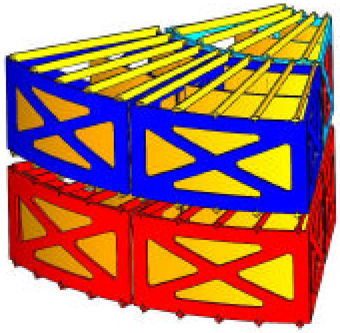
Inner Module (P&S)
Objective: Evaluate tooling and alignment techniques for mass production, X-ray test

Prototype Outer Pathfinder



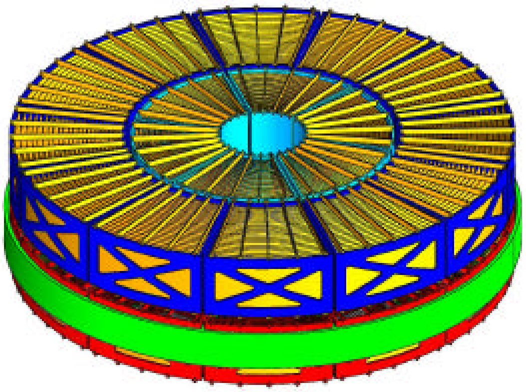
Outer modules (P&S) Largest Reflectors
Objective: Evaluate flight-like configuration outer module, X-ray and environmental test

Prototype Unit



Two outer modules + one Inner module (P&S)
Objective: Evaluate flight-like subassembly, X-ray and environmental test

Flight Mirror Assembly (FMA)



SXT Technology Development – Status

- Status summarized in 2003 SPIE papers
- Development has centered on 50 cm diameter engineering testbeds with 8.4 m focal length
  - Utilizes available metal mandrels and preparation facilities (coating & cleaning)
- Substantial progress toward making 50 cm diameter reflector segments that meet requirements
  - Reflector fabrication is key issue to meeting angular resolution requirement
  - Fabrication of acceptable reflectors requires accurately figured forming mandrels
    - Reflector quality is now limited by forming mandrel quality
    - Forming and replication require dust-free environment
  - Modified epoxy application approach - applied as axial strips; reduction of thickness
  - Knowledge of reflector quality is currently limited by ability to mount reflectors for metrology
    - Low stress mounts are yielding reproducable measurements
    - Still lack ability to map free standing reflector in three dimensions
- Forming mandrel requirements (figure, material) evolving along with reflector production process
- Replication mandrels fabricated by Zeiss meet figure requirements (not necessarily goal)
- OAP1 work demonstrated ability to reproducibly manipulate and align reflectors
- OAP2 used to develop reflector bonding scheme

Technology Goals for Coming Year

- Continue improving 50 cm diameter reflector figure - key to success
  - Refinement of forming - more uniform temperature
  - Obtain forming mandrels with 2 - 4 arcsec figure
  - Reduce epoxy thickness
  - Develop means of 3D mapping of free standing reflector
- X-ray and environmental tests of reflector pair (in OAP2 housing)
- Construct Engineering Unit
  - Current design details carried in reference mechanical design
- Develop automated alignment scheme
  - Incorporate CDA measurements into computer-controlled feedback loop for reflector alignment
- Upgrade facility for producing 1.6 m diameter reflectors
  - Replication and coating chambers have been ordered

Variables for FMA Study

- Number and size of mirror modules
  - Reference approach is one of many possibilities
  - Fundamental limitation is reflector size
- Grating mounting configuration
  - Monolithic unit (GIS) that can be integrated and tested with mirror module
- Reflector spacing
  - Existing design has some extra spacing between reflectors
  - Trade between field of view uniformity and on axis area

Current FMA Reference Concept Open Items

- Reference Concept is continually evolving
- Most recent analyses indicated Current Concept has marginal effective area and high mechanical loads on reflectors
- Effective Area
  - System Study Contractors to study minimization of obscurations, etc.
  - Project investigating several options to further increase area outside Study Contract
- Reflector
  - Project investigating options to reduce loads or reflector strengthening options
  - Systems Study Contractors to study minimization of loads propagating through reflectors

Constellation X

The Constellation X-ray Mission

FMA Systems

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Outline

- FMA Requirements Definition and Reference Concept
- Summary of Driving FMA Requirements
- Angular resolution
  - Mission Angular Resolution Error Budgets for requirement and goal
  - FMA Reference Resolution Budgets for requirement and goal
- Effective area
  - Derivation of FMA Requirement from Mission Requirement
  - FMA Reference Area Calculations
- Interfaces
  - Alignment
  - Grating Module

FMA Requirements and Reference Concept

- FMA Requirements have been derived in context of the Mission Reference Configuration and Mission Top Level Requirements
  – Applicable to FMA Study contract
  – Available in FMA Requirements Document

- FMA Requirements to be used for the study include
  – Performance (from Mission Performance Requirements)
  – Interface and Implementation (from Reference Observatory configuration)
  – Grating Module Accommodation (assuming in-plane reflection gratings)
  – Reflector Constraints (based on projected technology development)
  – Programmatic Assumptions

- FMA Reference Concept is provided as a basis or starting point for contractor work
  – Includes derived requirements and error budgets for Reference (may be changed by study contractor)
  – Requires optimization to fully meet FMA Performance Requirements

Driving FMA Requirements

FMA Performance Requirements		Source/Notes
Band Pass	0.25 to 10 keV	From Top Level Mission Band Pass
Effective Area	9630 cm^2 at 0.25 keV	From Top Level Mission Effecitve Area allowing losses for non-FMA contributors
	7250 cm^2 at 1.25 keV	
	1730 cm^2 at 6 keV	
	380 cm^2 at 10 keV	
Angular Resolution	12.5 arcsec HPD	
Field of View	2.5 arcmin radius	95% of on-axis area @1.25 keV
Implementation Requirements		
Focal Length	~10 m	limited by launch vehicle fairing
Envelope	1.68 m dia x 1.98 m long	limited by launch vehicle fairing
Mass	750 kg	from mission mass allocation
Power	400 watts average	from observatory power allocation
Thermal Control	Consistent with angular resolution spec's	
Grating Module Accommodation		
Grating modules	100	In-plane technology, size constrained
Reflector Constraints		
Length/arc width	20 cm/41.5 cm maximum	limited by projected technology
Thickness	0.41 mm ± .0.03 mm	limited by projected technology
Angular Resolution for P-S reflector pair	9.9 arcsec HPD	limited by projected technology

Angular Resolution Error Budget

- Mission angular resolution error budgets provided for both requirement and goal
- Mission Requirement of 15 arcsec HPD
  - ⇨ FMA Requirement of 12.5 arcsec HPD
  - ⇨ Reflector Constraint of 9.9 arcsec HPD for P-S pair
- Mission Goal of 5 arcsec HPD
  - ⇨ FMA Requirement of 4 arcsec HPD
  - ⇨ Reflector Constraint of 3 arcsec HPD

FMA Requirement — Angular Resolution

- On-orbit angular resolution: 12.5 arc seconds Half Power Diameter (HPD), exclusive of the following non-FMA effects:
  - Telescope effects including image re-construction, mounting strain, vibration, and instrument to FMA misalignments.
- The FMA Angular Resolution performance shall include all FMA driven sources of error, including (but not be limited to) :
  - Reflector figure errors, constrained for this study
  - Assembly and alignment errors
  - Gravity release errors
  - Launch induced errors
  - On-orbit FMA thermal errors
  - Material stability effects
- Angular resolution error budget

Mission Angular Resolution Error Budget – Requirement

ITEM (HPD - arcsec)	RQMT	Margin	Pred	Allocation				
RGS Resolution	15.00	4.48	14.32					
Co-add 4 satellites				1.00				
On-Orbit Telescope - single satellite				14.28				
CCD pixelization error					0.41			
Grating Resolution Errors					5.00			
Calorimeter Resolution	15.00	5.34	14.02					
Co-add 4 satellites				1.00				
On-Orbit Telescope - single satellite				13.98				
Calorimeter pixelization error					4.08			
Telescope level effects					4.80			
Image Reconstruction errors (over obs)						4.24		
Attitude knowledge drift							3.00	
FMA/XMS focal plane drift (thermal)							3.00	
FMA/XMS vibration effects						2.00		
FMA/XMS misalignment (off-axis error)						1.00		
FMA/XMS Focus Error						0.20		
FMA On-orbit performance					12.48			

FMA Reference Concept Angular Resolution Error Budget – Requirement

ITEM (HPD - arcsec)	RQMT			PRED	Allocation		
FMA On-orbit performance	12.5			12.48			
SXT Mirror launch shifts					2.00		
On-orbit Thermally Driven Errors					2.24		
Bulk temperature effects						1.00	
Gradient effects						2.00	
Material stability effects					1.00		
FMA/Telescope mounting strain					1.00		
FMA, As built					12.03		
Gravity Release						1.50	
Bonding Strain						2.00	
Module to Module alignment (using CDA)						2.00	
P-S alignment in module(using CDA)						3.38	
CDA Dynamic Accuracy							0.76
CDA Static Static Accuracy							1.68
Thermal Drift							2.00
Adjustment Accuracy							2.00
Reflector Housing Installation/Focus Correction						5.00	
(correction of radius and cone angle)							
Reflector Pair (P-S)						9.90	
	Rqmt		Margin	RSS Predict		Allocation	

FMA Reference Angular Resolution Error Budget Comments

- 12.5 arcsec HPD required at FMA level
- Reflector pair (P+S) budgeted at 9.9 arcsec HPD
  - Uncorrected reflector will have focus error
  - Assumes that alignment system corrects for average radius and cone angle which, due to manufacturing limitations, have large tolerances
  - Error budget assumes NO sag correction
- Reflector installation into mirror submodule housing and focus correction (5.00 arcsec)
  - Bend reflector to correct radius and cone angle to achieve FMA design focus (introduces other figure errors)
  - Other distortions due to installation
- P-S alignment in module (3.38 arcsec) includes:
  - CDA measurement errors
  - Errors in adjusting the individual CDA centroids to a common point, at the correct focal distance
  - Alignment process corrects average slopes at azimuths sensed by CDA
- Housing-to-housing (2 arcsec)
  - Errors in aligning all six P-S housings to a common point, using CDA

Mission Angular Resolution Error Budget – Goal

ITEM (HPD - arcsec)	Goal	Margin	Pred	Allocation				
Calorimeter Resolution	5.00	0.87	4.92					
Co-add 4 satellites				1.00				
On-Orbit Telescope - single satellite				4.82				
Calorimeter pixelization error					1.63			
Telescope level effects					1.53			
Image Reconstruction errors (over obs)						1.41		
Attitude knowledge drift							1.00	
FMA/XMS focal plane drift (thermal)							1.00	
FMA/XMS vibration effects						0.20		
FMA/XMS misalignment (off-axis error)						0.50		
FMA/XMS Focus Error						0.20		
FMA On-orbit performance					4.27			
SXT Mirror launch shifts						0.50		
On-orbit Thermally Driven Errors						1.41		
Bulk temperature effects							1.00	
Gradient effects							1.00	
Material stability effects						1.00		
FMA/Telescope mounting strain						1.00		
FMA, As built						3.74		
Gravity Release							1.00	
Bonding Strain							1.00	
Housing to Housing alignment (using CDA)							1.00	
P-S alignment in module(using CDA)							1.00	
CDA Dynamic Accuracy								0.50
CDA Static Static Accuracy								0.50
Thermal Drift								0.50
Adjustment Accuracy								0.50
Reflector Installation in Sub-module Housing							1.00	
(correction of radius and cone angle)								
Reflector Pair (P-S)							3.00	
	Goal		Margin		RSS Predict		Allocation	

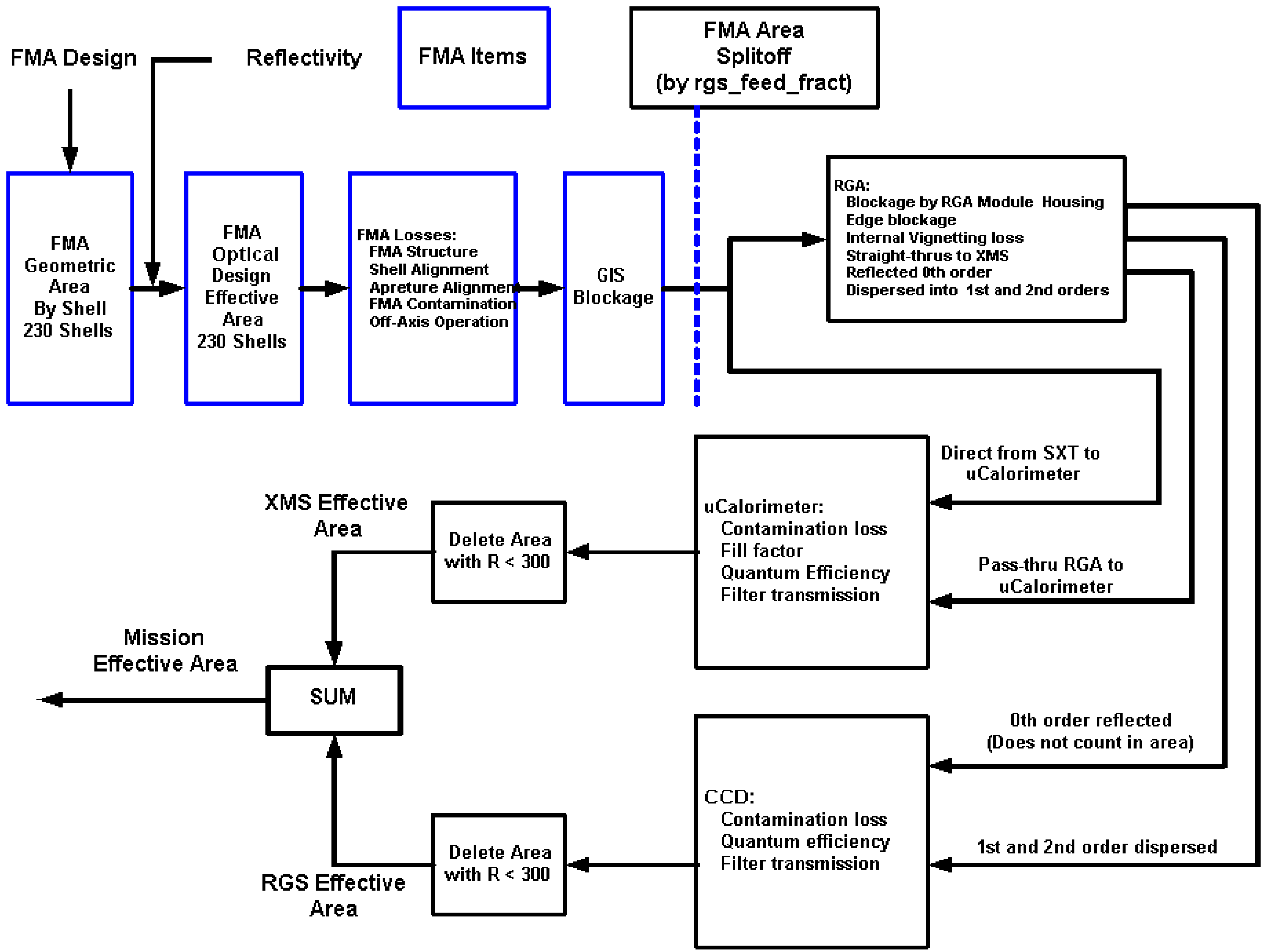
Mission Design Reference Effective Area

- Mission level effective area requirements met by combining SXT's from four observatories.
- Mission effective area depends on many factors, including:
  - FMA effective area
  - Grating design and efficiencies
  - CCD detector (RFC)
  - Calorimeter performance (XMS)
- FMA effective area depends on
  - FMA Optical design
  - FMA Optics and coatings
  - FMA level losses such as structural blockage
  - Grating Integrating Structure blockage
- FMA Requirement document defines FMA effective area requirements
- This briefing summarizes the effective area calculation methodology and needed data

FMA Requirements — Effective Area Assumptions

- **The minimum on-axis effective area for each FMA shall be:**
  - 9630 cm2 at 0.25 keV
  - 7250 cm2 at 1.25 keV
  - 1730 cm2 at 6 keV
  - 380 cm2 at 10 keV
- **The FMA effective area shall account for the following losses:**
  - FMA housing structural obscurations
  - Grating support structure (GIS) obscurations
  - X-ray reflectivity of mirror coatings
  - Contamination to optical surfaces
  - P Reflector to S Reflector alignment losses
  - Reflector to collimator alignment losses
  - Losses due to mis-alignment between the FMA optical axis and telescope axis
- **The FMA effective area DOES NOT include the losses due to the gratings or the grating module structure**

SXT FMA Reference Concept Effective Area Calculation Flow



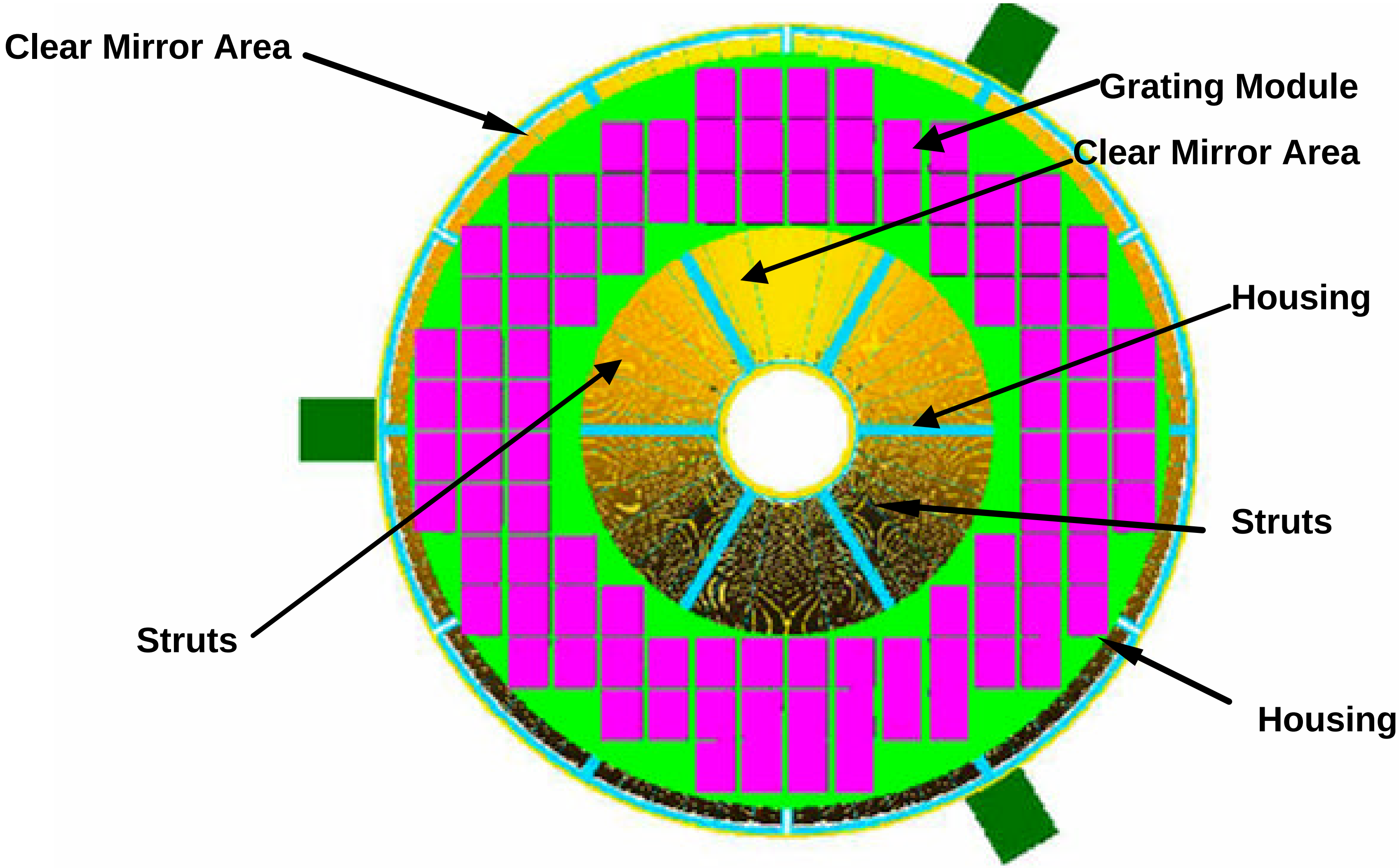
FMA Reference Concept Area Losses

- Reflectors omitted from design to use volume for housing structure
  - Shells 90-103
- Structure obscurations (~8-14% depending on shell)
  - Housing and Mirror Support Struts
- Primary to Secondary Reflector misalignment (1% depending on shell)
- Reflector-to-aperture misalignment (0.5% to 1%, depending on shell)
- Off-axis operation (assume 0.5% depending on shell)
  - Due to optical axis mis-alignment
- FMA end of life contamination (1%)
- Area covered by GIS (5% of reflectors covered by operating modules)

Grating Assumptions (Design Reference Calculation)

- 100 grating modules partially cover outer reflectors (shells 1 – 89)
- GIS loss estimated as 5% of area covered by grating modules
- Other grating losses help drive FMA requirement but are NOT included in FMA Effective Area
  - Grating module structural blockage and alignment loss:
    - Grating module walls cause 10% loss (of area covered by modules)
    - Grating edges cause 6.1% loss (of area covered by modules)
  - In-plane grating division of input light:
    - 57% to 60% is dispersed to 0th, 1st and 2nd grating orders, depending on energy
    - 38% to 40% goes straight-through to XMS, depending on energy
    - 0% to 5% is lost due to internal vignetting, depending on energy

FMA Reference Concept – RGS Configuration



Grating placement can be optimized

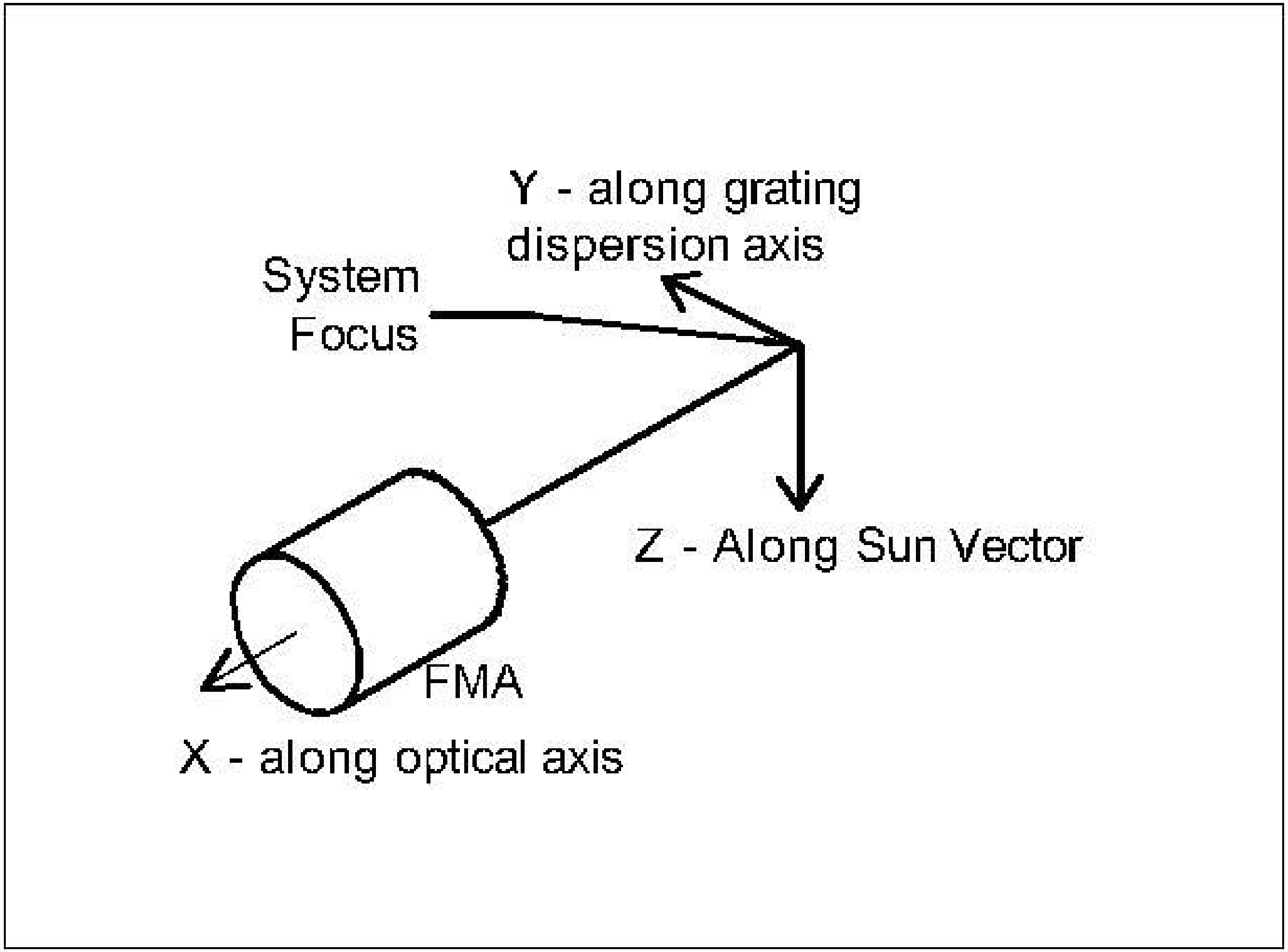
FMA Reference Concept Effective Area Estimate

FMA Effective Area		Energy(keV)		
	0.25	1.25	6	10
Geometric Area	14854	14854	14854	14854
Effective Area Base	10575	10190	2269	791
Structural Blockage Loss	1544	1499	501	104
Shell Alignment Loss	90	86	18	7
Aperture Alignment Loss	64	62	17	7
Contamination Loss	99	96	20	8
Off-axis Loss	40	38	8	3
GIS Structure Blockage	368	351	11	0
FMA Reference Design EA	8370	8058	1694	662
FMA Specification EA	9630	7250	1730	380
FMA Reference Design Margin(%)	-13.1	11.1	-2.1	74.3

FMA Requirements: Mounting and Alignment

- External Mechanical Interface
  - Three point kinematic mount to telescope (see J. Stewart presentation)
- FMA External Alignment and Alignment Interfaces
  - The FMA must be installed into the Observatory and aligned with the RFC and XMS.
  - The optical axes of the FMA and HXT's must be co-aligned so that they point in the same direction. (Align HXT to FMA)
  - Alignments must be stable through launch and on-orbit operations.
- Provide alignment reference (or references) for the following:
  - Location of focus position in three translational degrees of freedom, accurate to ±0.5mm in the lateral axes (Y and Z), and to ±1mm axially (X axis)
  - Orientation of optical axis (line from mirror node to mirror focus), accurate to within ±10 arcsec.
  - Clocking reference angle (rotation of FMA about optical axis), accurate to ±5 arcmin.
- FMA Alignment Stability – Launch shifts and On-orbit
  - Launch shift of the FMA optical axis shall be no more than ±10 arcsec.
  - On-orbit, the optical axis of FMA stable to within 2 arcsec.
    - Based on image reconstruction error budget

FMA Coordinate System



FMA Requirements: Grating Module Interfaces

- **Provide a "Grating Integrating Structure" (GIS) to support grating modules:**
  - GIS may be one or more monolithic, separable structures or an integral part of the FMA
  - Mass counts in FMA mass allocation
  - Grating modules partially cover outer reflectors only
- **GIS must support alignment requirements as stated by K. Flanagan**

Constellation X
The Constellation X-ray Mission

FMA Reference Concept Optical Design

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Outline

- FMA Optical Design Requirements
  - Optical Performance Requirements
  - Implementation Requirements
- FMA Reference Concept Optical Design Requirements
- Optical Design Options
- FMA Reference Concept Optical Design
  - Physical size
  - On-axis and off-axis effective area
  - Optical performance
  - Stray light issues

FMA Optical Performance Requirements

- From FMA Requirements Document

	Requirement
Bandpass	0.25 to 10 keV
Number of Mirrors (per mission)	4
On-axis effective area (per mirror)	
@0.25keV	9630 cm^2
@1.25 keV	7250 cm^2
@6.00 keV	1730 cm^2
@10.00 keV	380 cm^2
Angular resolution	12.5 arcsec (HPD)
Field of view	2.5 arcmin radius at 95% effective area at 1.25 keV

FMA Implementation Requirements Driving Optical Design

- From FMA Requirements Document

	Requirement
Axial focal length	10,000 mm ± 5 mm
Maximum envelope length*	1.98 m
Maximum diameter	1.68 m dia
Optical design	Wolter I

**Includes space for gratings, collimators, etc.*

Derived Requirements for FMA Reference Concept Optical Requirements and Design

Parameter	Value	Source
Axial focal length	10 m	Effective area, Max design envelope
Radial diameter range	0.3 – 1.6 m**	Effective area, Max design envelope
Reflector axial length	200 mm	Reflector fabrication and mounting considerations
Primary-Secondary separation	50 mm	Mirror housing accommodation
Reflector radial thickness	0.41 mm	Reflector fabrication considerations, mass
Unobstructed field-of-view	2.5 arcmin* dia	Off-axis effective area
Reflector radial placement	0.23 mm	Reflector alignment , housing requirement

** Different from current FMA Requirements Document*
***At primary-secondary intersection plane*

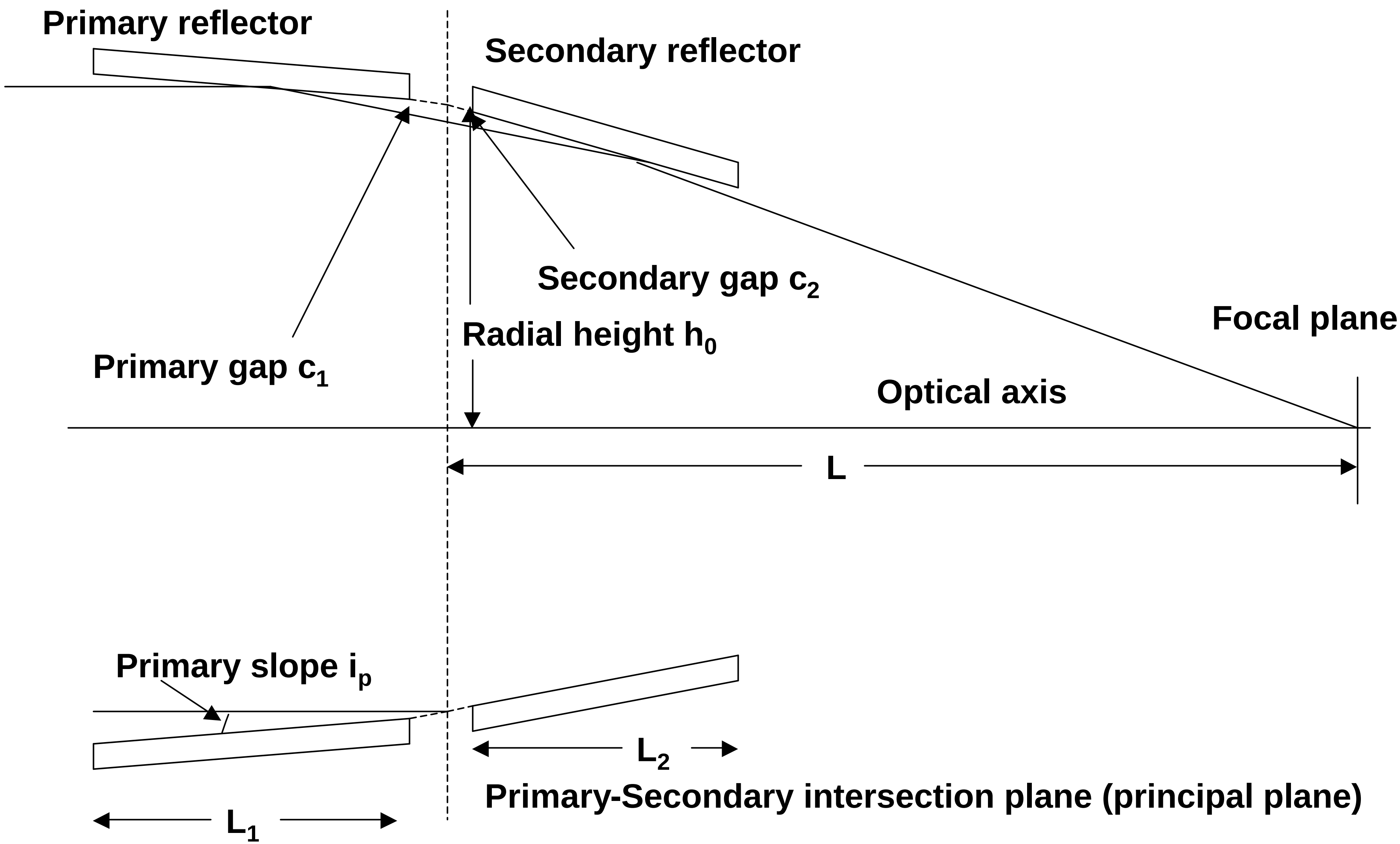
FMA Optical Design Options

- Requirement for this Study: Wolter Type I Mirrors
- Viable Alternative: Equal – Curvature Mirrors
- Options not Practical for FMA
  - Cone-Cone mirrors
  - Wolter-Schwarzschild mirrors
  - Hyperboloid-hyperboloid mirrors
  - Polynomial mirrors

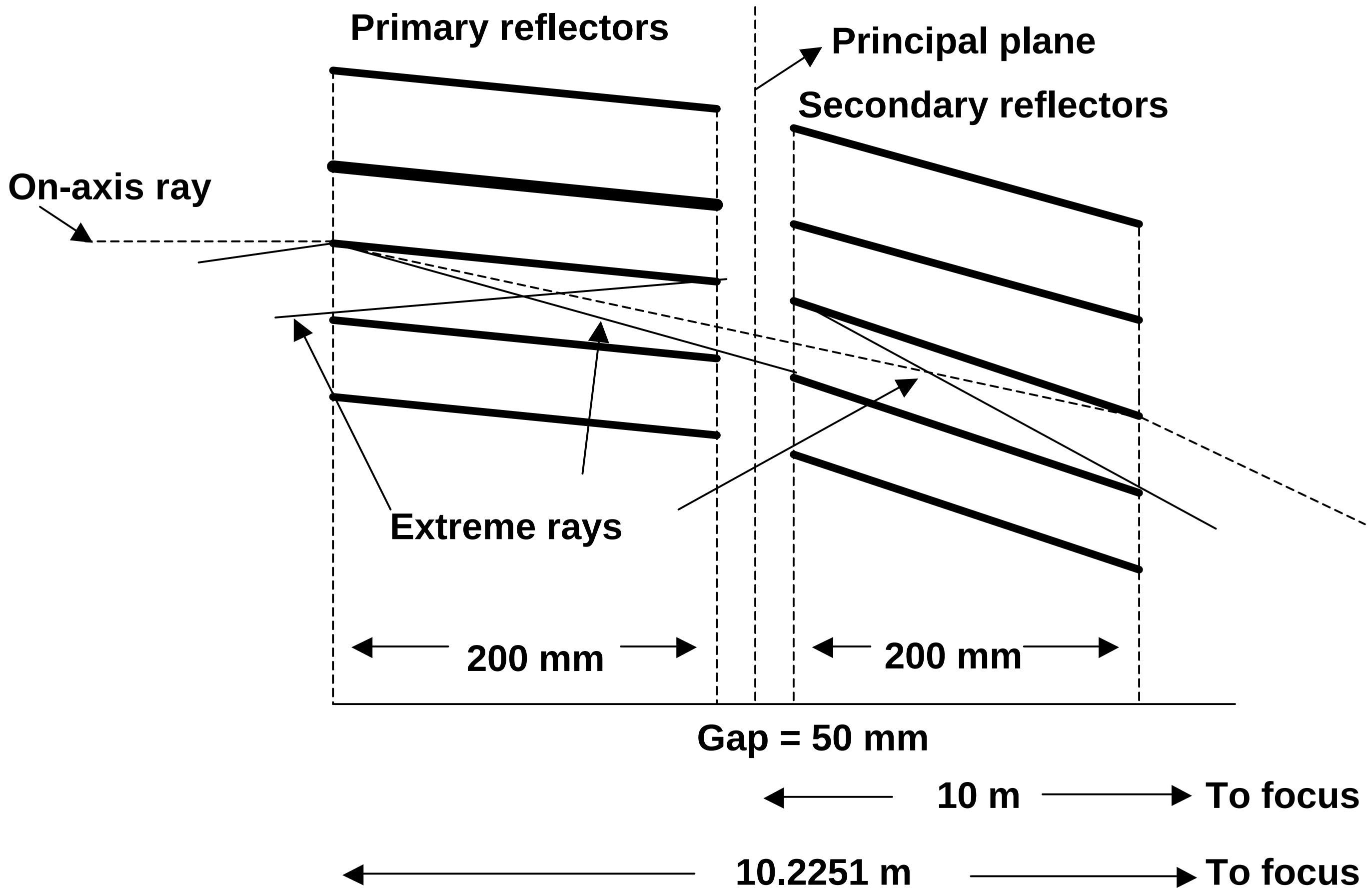
FMA Optical Design Principles

- Maximize on-axis effective area
  - Grazing angle of the primary and secondary the same at the intersection point of the reflectors
  - Secondary reflector placed optimally to prevent on-axis vignetting
- Off-axis effective area
  - Primary and secondary reflector axial length the same
  - Off-axis vignetting allowed

FMA Optical Design Parameters



Design Principles for Nested FMA Mirror



FMA Reference Concept Optical Design Physical Size

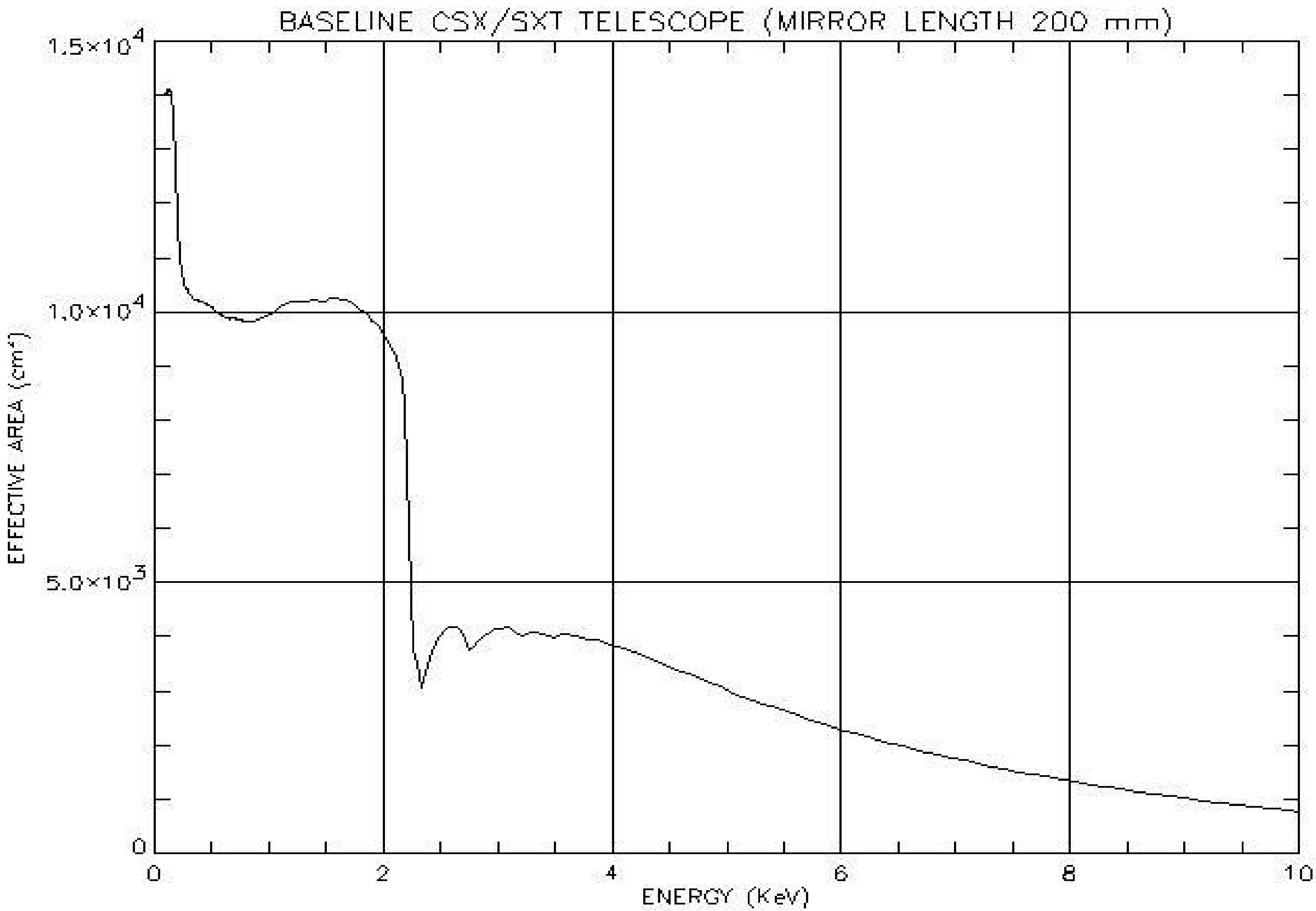
	Value
Axial focal length (m)	10.0
Number of shells	230*
Primary/Secondary reflector axial length (mm)	**200.0**
Primary/Secondary gap (mm)	25.1 / 24.9
Primary outer reflector max/min radial height (mm)	804.480 / 800.500
Primary Inner reflector max/min radial height (mm)	151.431 / 150.680
Principal plane max/min radial height (mm)	800.000 / 150.596
Secondary outer reflector max/min radial height (mm)	798.507 / 786.506
Secondary inner reflector max/min radial height (mm)	150.304 / 148.433

Of these shells, 90-103 blocked by the mirror housing modules

Assumptions for FMA Optical Design Effective Area Calculations

- Gold coating
- No aperture obscurations or contamination losses included
- Use atomic scattering factors from LBL web site (see Ref. page)
- Gold density of 16.965 gm/cm3 (90% of bulk)

FMA Reference Concept Optical Design Effective Area



Does not include losses from omitted reflectors, structural obscurations, reflector misalignment, Grating Integration Structure (GIS) or contamination

FMA Reference Concept Optical Design Effective Area

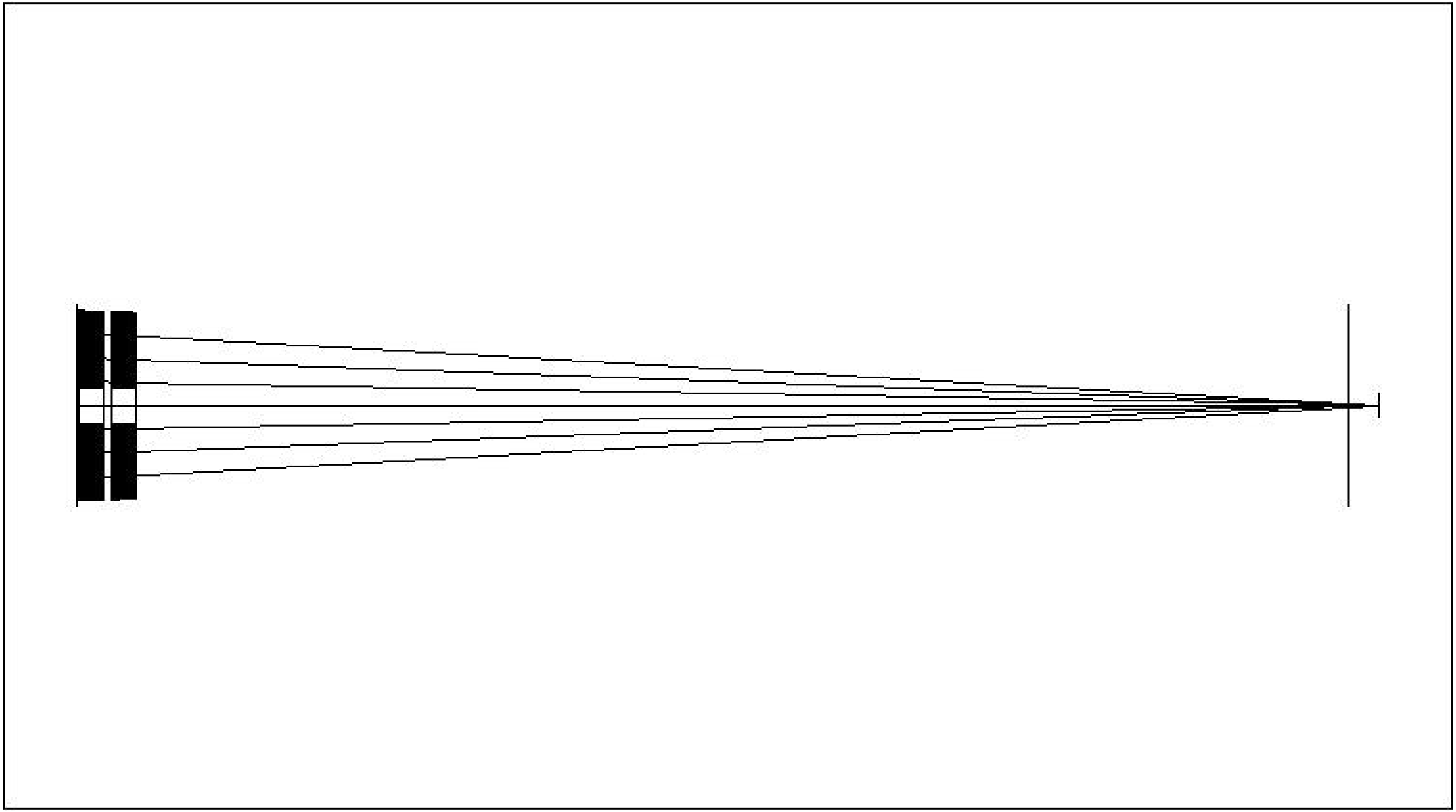
- Number of shells = 230 Reflector length = 200 mm

Energy (keV)	Reference FMA Optical Design Effective area (cm^2)*	FMA Effective Area Requirement (cm^2)	Margin available for other FMA loss factors (%)
0.25	10571	9630	10
1.25	10190	7250	41
6.0	2269	1730	31
10.0	760	380	100

***Does not include losses from omitted reflectors, structural obscurations, reflector misalignment, Grating Integration Structure (GIS) or contamination**

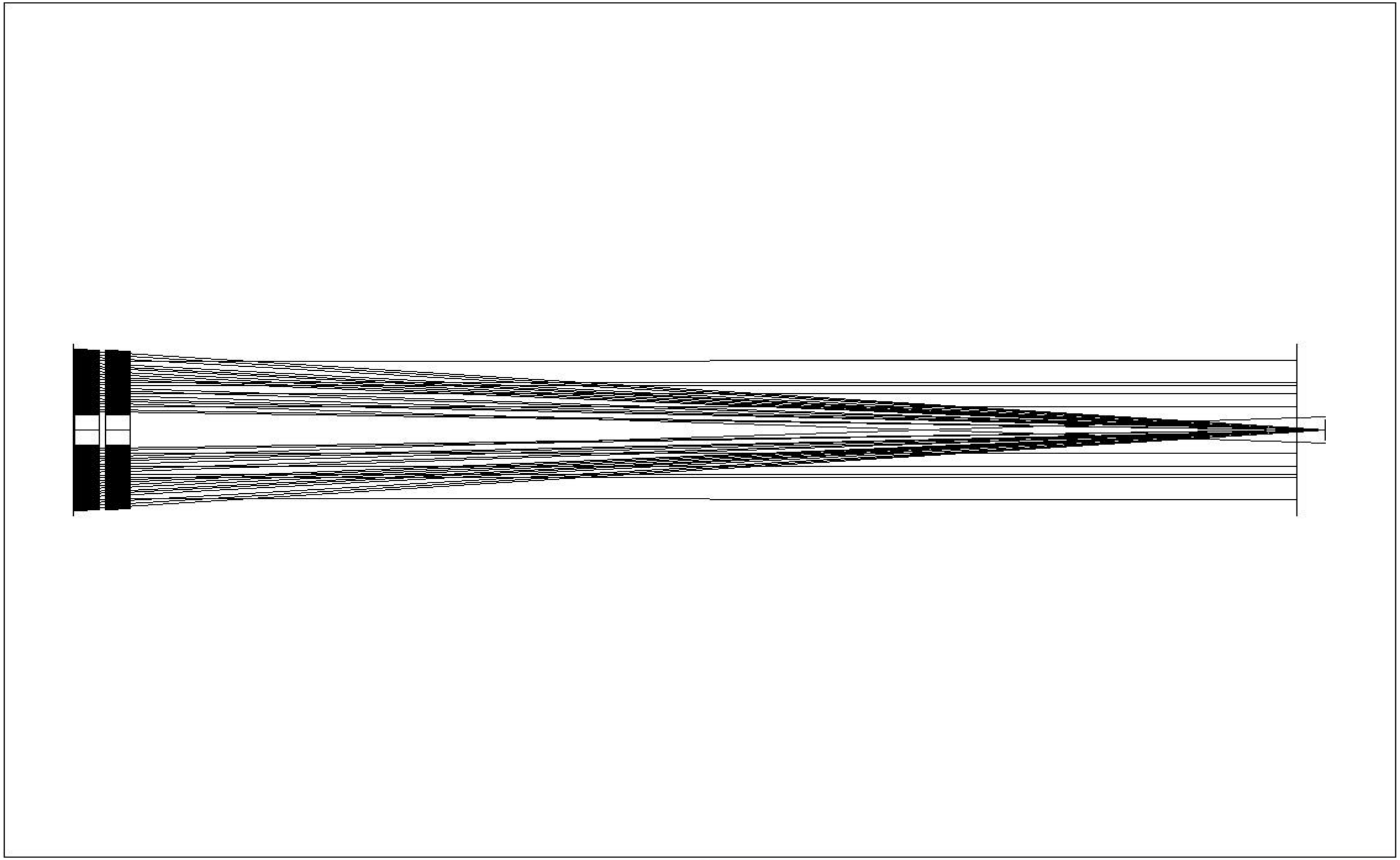
ZEMAX Model for FMA Reference Concept Optical Design

- Number of shells = 230 Reflector length = 200 mm



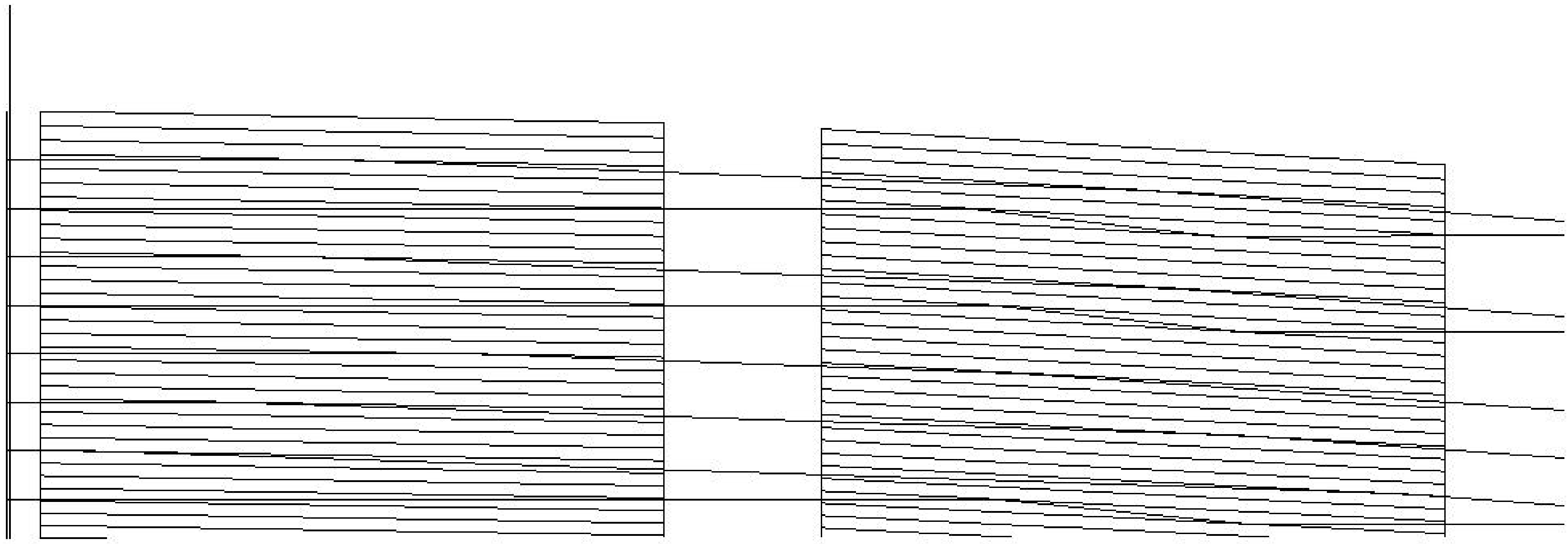
Straylight in FMA Reference Concept Optical Design

- Number of shells = 230 Reflector length = 200 mm



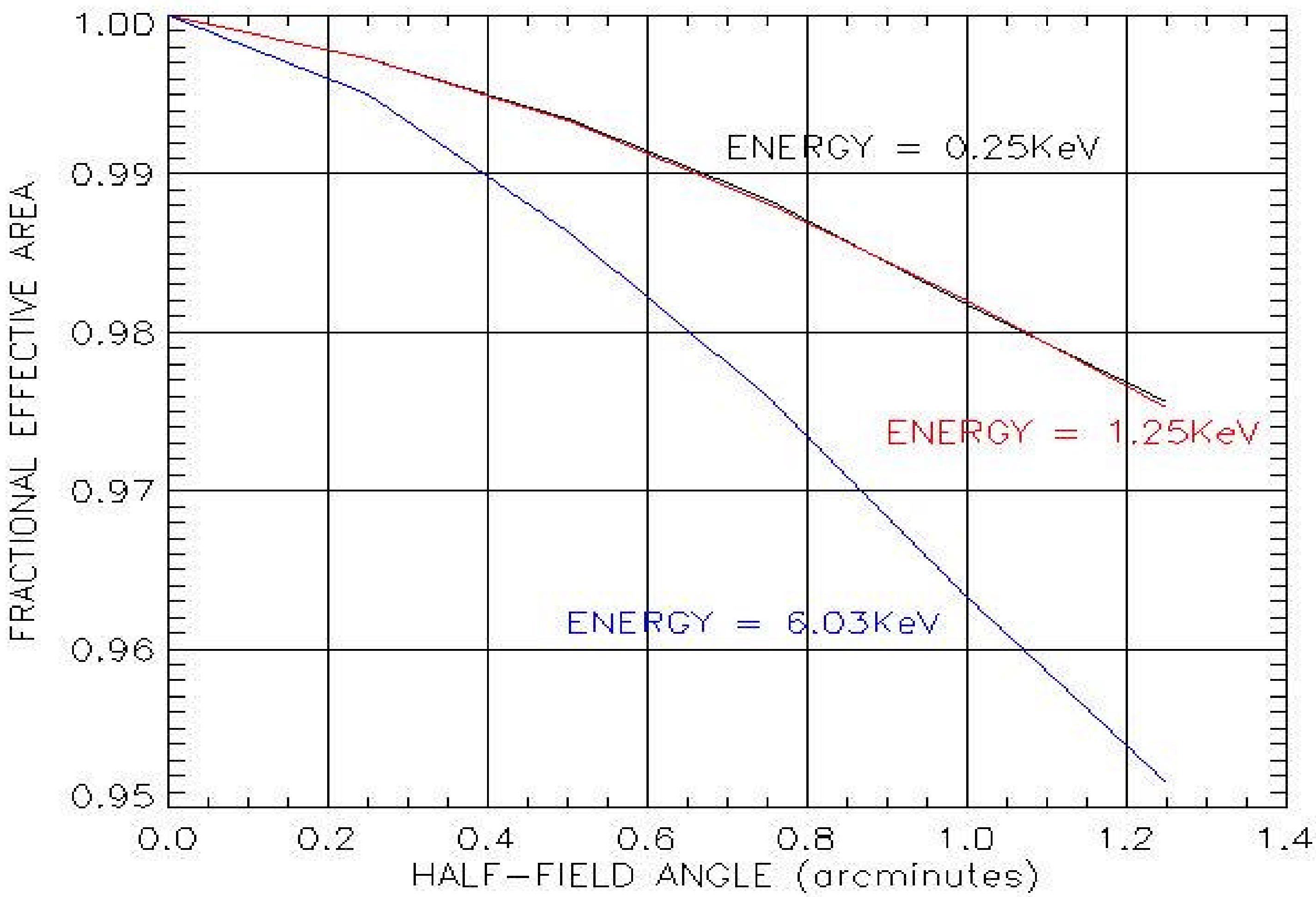
Straylight in FMA Reference Concept Optical Design

- Number of shells = 230 Reflector length = 200 mm



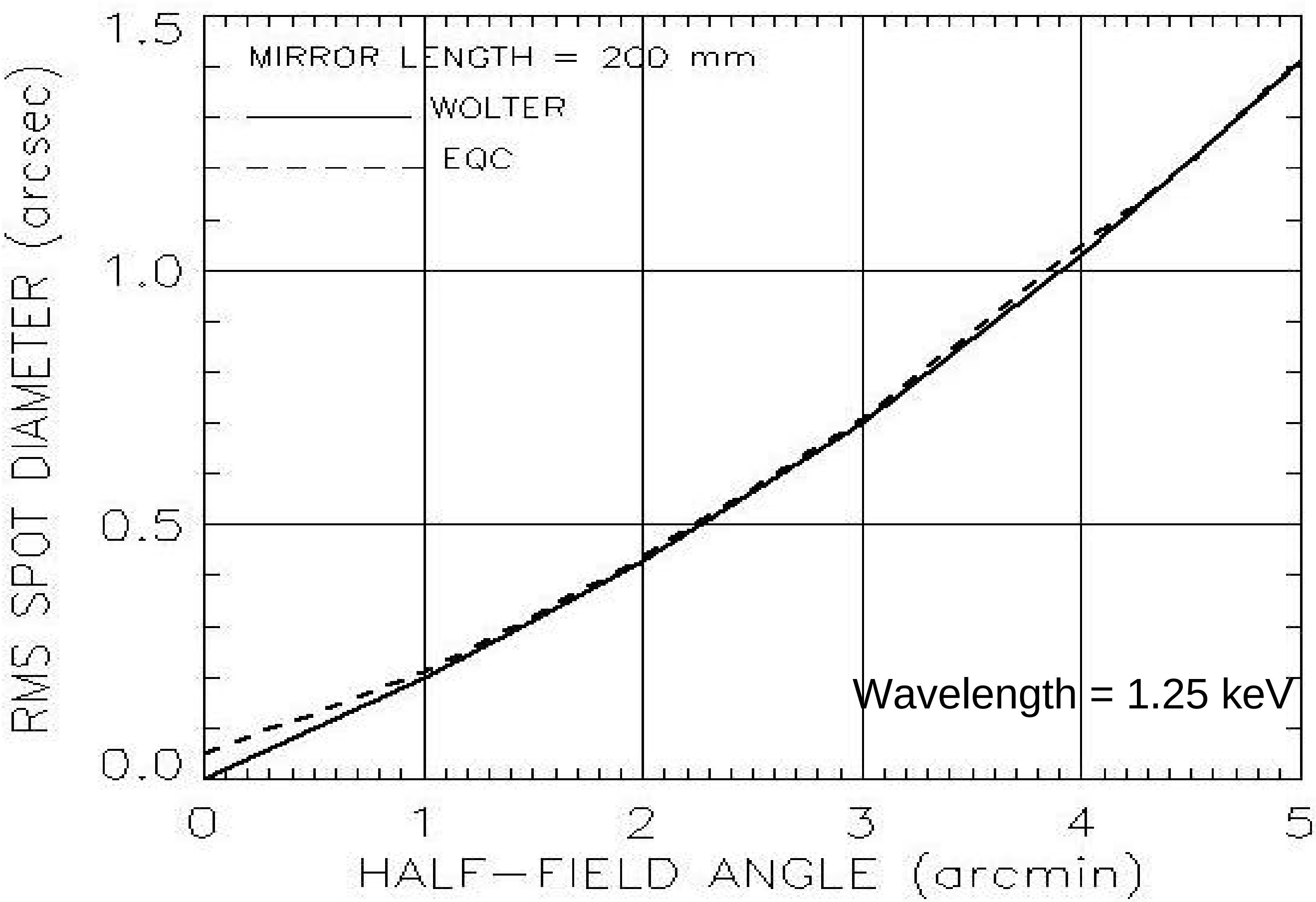
FMA Reference Concept Optical Design Off-axis Effective Area

- Number of shells = 230 Reflector length = 200 mm



Optical Performance of FMA Reference Concept Optical Design

- Wolter mirror design versus Equal-Curvature mirror design
- On-axis HPD requirement = 12.5 arcsec



Reference Documents/Memos

- Memos
  - CSX/STX telescope design data for 200 mm and 300 mm long mirrors, May 21, 2002
  - Off-axis data and effective area data for new CSX/SXT designs, May 31, 2002
- Published papers
  - T.Saha and W. Zhang," Equal-Curvature Grazing-incidence X-ray Telescopes," Appl. Opt, 42, 4599-4605 (2003)
  - T.Saha, W.Zhang, and D.Content,"Equal-Curvature X-ray Telescope Designs for Constellation-X Mission," Proceedings of SPIE, 5168-37 (2003)
- Gold optical constants
  - http://cindy.lbl.gov/metrology/opticalconstant.html
  - Updated data (1994)

SXT FMA Industry Study Pre-Bidder's Conference — Nov. 5, 2003

Constellation X
The Constellation X-ray Mission

Reflector Technology

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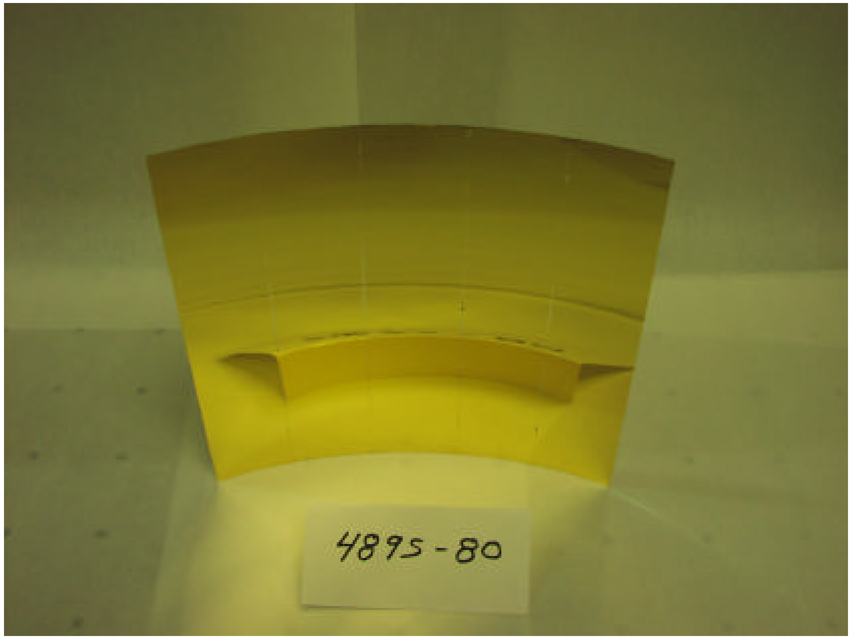
Outline

- Introduction
- Requirements Imposed on the Alignment/Integration Process
- Reflector Material Properties
- Reflector Optical Properties
- Reflector Physical Sizes
- Fabrication of Reflectors
  - Forming mandrels
  - Forming mandrel treatment
  - Slumping
  - Post-slumping trimming
  - Metrology of the substrate
  - Epoxy replication
  - Metrology of the reflector



An SXT Reflector

Introduction

- Reflector development and fabrication are not part of this FMA Study.
- The FMA Contractors are to assume for the purpose of this study that the reflectors will be provided meeting certain requirements, some of which are directly derived from the Constellation-X mission requirements and others from reasonable assumptions.
- This presentation has two parts
  - Information that the FMA Contractor shall take as input to, and constraints on, their FMA systems study and design. Their alignment and integration process must be compatible with, and accommodate, the properties and characteristics of the reflectors.
  - Description of the reflector development and fabrication process that helps the Contractors to place the above information in context.

Requirements Imposed on the Alignment/Integration Process

- Practical Difficulties
  - Given the flimsy nature of the reflectors, it is extremely difficult to measure or qualify their intrinsic parameters, such as average radius and cone angle, to the required accuracy
  - Because of distortion caused by gravity, the reflector cannot be kinematically mounted and expected to have required optical figure
  - For the same reason, it is extremely difficult to handle, or mount, the reflector without causing significant distortion
- Solutions/Requirements Imposed on the Alignment/Integration Process
  - The reflector will always be over-constrained
  - The overconstraints must not introduce additional figure errors beyond budget
  - The overconstraints must be capable of correcting two errors that the reflector will have by design
    - Average radius error: from a tolerance of ±0.1mm to ±0.01mm
    - Cone angle error: ±20 arcsec to better than ±0.5 arcsec

Reflector Material Properties

- **Reflector Materials List**
  (See Section 7 of FMA Requirements Document for all reflector constraints)
  - Glass substrate: Schott D263 glass sheets; composition similar to Pyrex (borosilicate)
    - 0.4 ± 0.02 mm in nominal thickness
    - CTE: 6.3 ppm K^{-1} at room temperature
    - Young's Modulus: 10.6 Mpsi at room temperature
  - Epoxy: Epotek 301 A/B
    - Thickness: 5 to 10mm
    - Relatively low outgas rate: 0.07% weight loss (200°C for 300 hrs)
    - Relatively low Young's modulus: ~248,000 psi at room temperature
    - Relatively low CTE: ~55 ppm K^{-1} at room temperature
    - Scotch-Weld 2216 A/B may be used in the future because of its lower modulus
  - Gold
    - Thickness: ~2000Å
    - Magnetron sputtered or evaporated

Optical Properties

- Cone Angle
  - The reflector will be fabricated to have a cone angle that is within 20 arcsec of the theoretical prescription. The Contactor’s alignment/integration system is required to be capable of correcting this 20 arcsec to ± 0.5 arcsec
- Average Radius
  - Within 0.1mm of the theoretical prescription. The Contactor’s alignment/integration system is required to be capable of correcting this average radius error.
- The reflectors will have
  - A 9.9 arcsec two-reflection image half-power-diameter (HPD)
  - 200 mm reflector axial length
- Axial Figure
  - Axial sag (P-V) within 0.18μm of the theoretical prescription, assuming correlation between the primary and secondary sag errors
  - Axial sag (P-V) within 0.60μm of the theoretical prescription, assuming no correlation between the primary and secondary sag errors
  - Axial sag (P-V) within about 1.2μm of the theoretical prescription, assuming anti-correlation between the primary and secondary sag errors
  - Axial slope error less than 2 arcsec rms after removing sag error
- Microroughness
  - 4Å rms measured over a length scale of 1 mm
- In-Phase Roundness
  - Within ±10μm of the theoretical prescription
- Out-of-Phase Roundness
  - Within ±0.5μm of the theoretical prescription

Reflector Dimensional Specifications

- **For the purpose of this study, the Contractor shall assume that reflectors will have the following dimensional specifications**
- **Final Reflector Geometry**
  - **Wolter-I surface sector**
  - **The largest reflector that can be supplied is no larger than 200mm in the optical axis direction and 415mm in the azimuthal arc length**
- **Dimensional Tolerance**
  - **Overall dimension within 500μm of mechanical engineering prescription**
- **Forward and Aft Edge Planarity**
  - **The forward (aft) edge will be within 25μm a plane perpendicular to the optical axis**
- **Reflector Thickness and Its Variation**
  - **Thickness: 0.41 mm**
  - **Thickness Variation:**
    - **Within a single reflector: ±10μm**
    - **Reflector to Reflector: ±30μm (dominated by batch to batch glass thickness variation)**

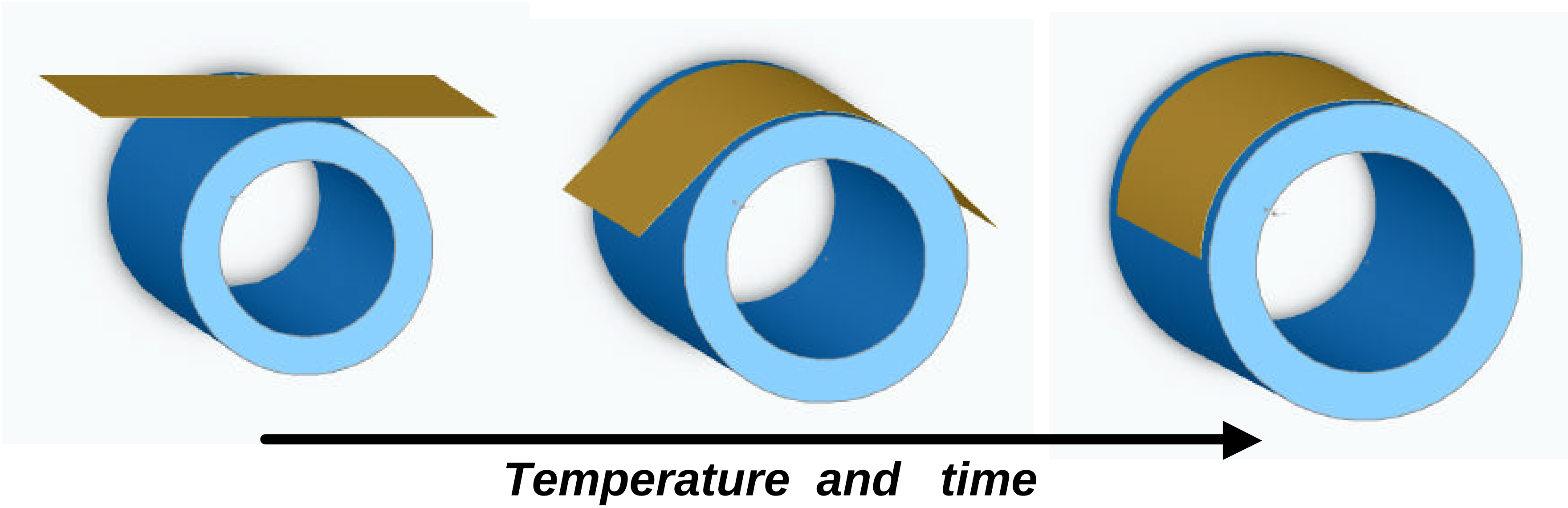
Reflector Fabrication Process

- **Substrate Forming**
  - Creating substrates conforming to the forming mandrel to better than 0.25μm
- **Substrate Post-Forming Trimming**
  - Cutting off edges that do not form well because of gravity and temperature gradients
  - Creating fracture-free edges to reduce probability of glass cracking
  - Creating accurate sizes for integration
- **Substrate Metrology and Qualification**
  - Axial figure measurements on an interferometer
  - 3-D figure using Coordinate Measuring Machines (CMM) with both contact and non-contact probes
- **Replication**
  - Smooth out figure errors that have spatial periods less than ~10mm.
  - Seal surface damages to prevent cracking
- **Post-Replication Metrology and Qualification**
  - Axial figure measurements to be compared with those of the substrates
  - 3-D figure measurements using CMM
  - Microroughness measurements to be compared with those of the mandrel

Mandrels for Making Reflectors

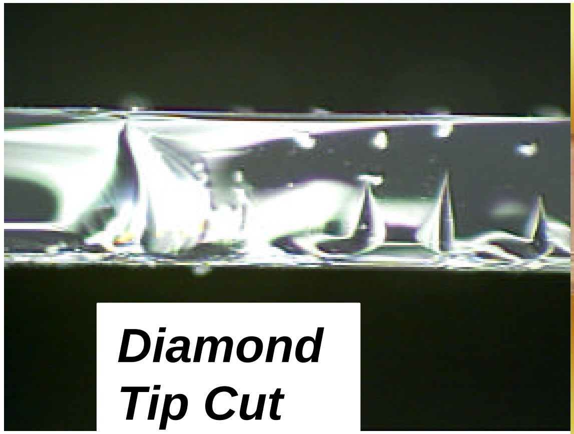
- Forming Mandrels
  - Total numbers: 216 primary, 216 secondary
  - Materials: Fused quartz and/or Zerodur K20
- Replication Mandrels
  - Total numbers: 75 primary, 75 secondary
    one mandrel for every three shells
  - Microroughness: ~3Å rms (length scale 0.3 mm)
  - Figure quality: 4 arcsec two-reflection half-power diameter equivalent
  - Capable of sustaining over 200 replications

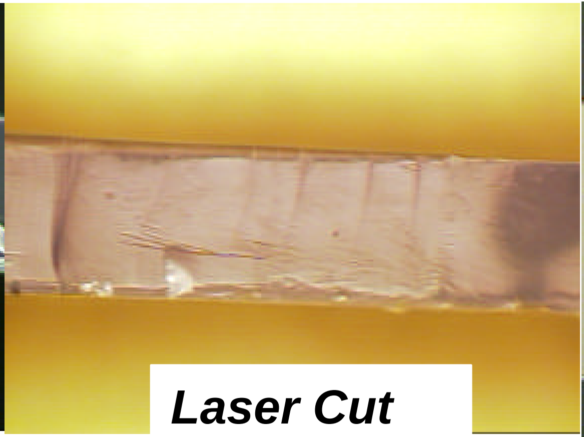
Substrate Forming Process

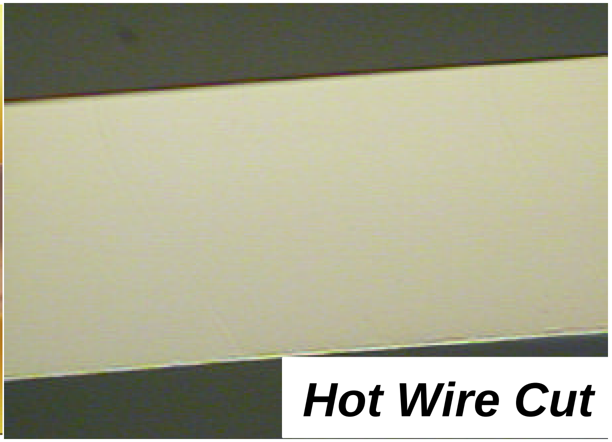


- Important Factors
  - Mandrel surface treatment prevents sticking and friction
  - Clean environment is essential. Dust particles trapped between the glass sheet and mandrel surface cause big holes on substrate surface
  - Maintaining temperature uniformity on the glass sheet is essential. Glass viscosity (elastic modulus) is a very sensitive function of temperature
  - Minimizing/eliminating forces (other than gravity) exerted on the glass sheet is essential

Post-Forming Trimming

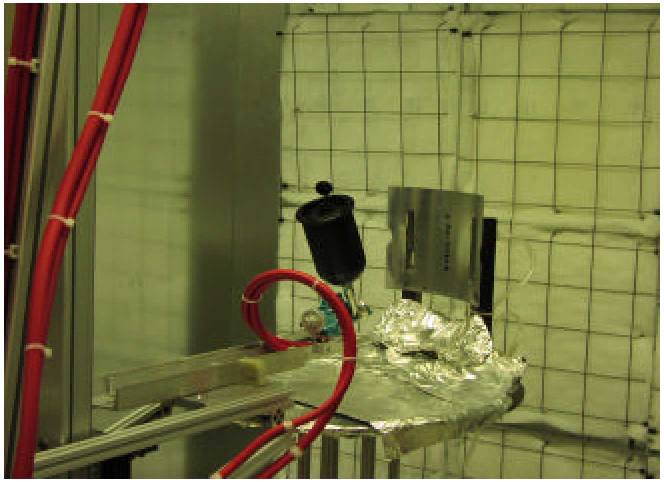




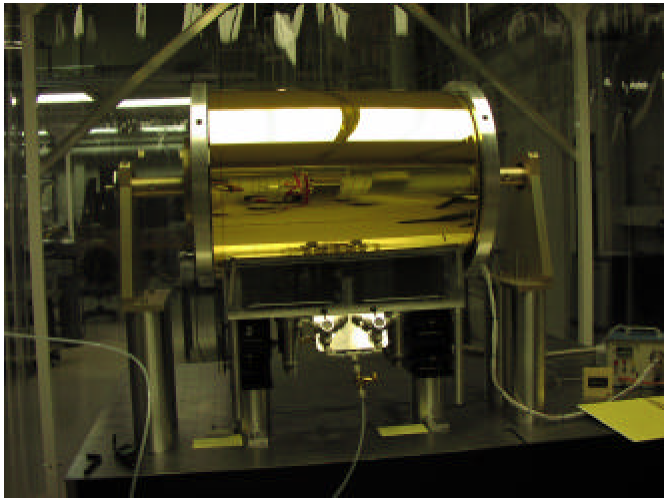


- **Remove about one inch of glass from all four sides which typically do not slump right because of temperature and gravity gradients**
- **Hot wire technique to achieve very smooth and fracture-free edges**
- **Reference to the figured mandrel surface to achieve precision edges**

Replication

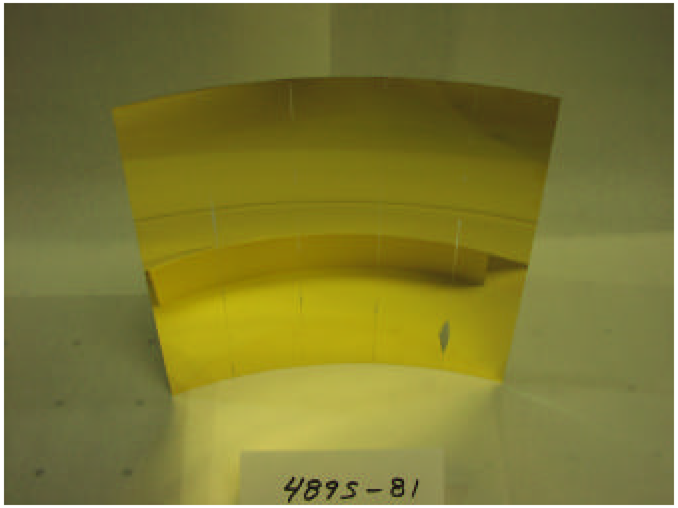


Epoxy Application on Substrate



Attach to Replication Mandrel in Vacuum

Separation of Replica from Mandrel



Finished Reflector

Important Factors of Replication

- Dust free environment is essential. Any dust particles trapped between the substrate and mandrel cause severe distortion.
- A thick layer of gold coating (~2000Å) is essential in eliminating pin holes
- Epoxy layer should be as thin as possible, but thick enough to eliminate mid/high spatial frequency errors on the substrate: current baseline 10mm, 5mm is being investigated. Thick epoxy layer causes distortion during cure as well as later when temperature excursion occurs.
- Segmented epoxy application substantially reduces overall distortion
- Mandrel cleaning: (1) preserve mandrel durability and (2) facilitate good microroughness for replica

SXT FMA Industry Study Pre-Bidder's Conference — Nov. 5, 2003

Constellation X

The Constellation X-ray Mission

Mechanical Design

Jeff Stewart/GSFC
Lead Mechanical Design Engineer
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Outline

- FMA Requirements and Objectives
- FMA Mechanical Design
  - Overall (Mirror Modules, Ring Structure Assembly)
  - Mirror Modules and Module Flexure Concept
  - CTE of FMA Materials
  - Strut Concept
  - FMA Design Option
  - Structural Analysis

FMA

Requirements and Objectives

FMA Requirements

Requirement		FMA Requirement Document Reference
FMA Envelope	**1.68 m** diameter, **1.98 m** length	Structure Design
FMA Mass	**<750 kg**	Structure Design
FMA First Mode Frequency	**>50 Hz**	Structure Design
Internal Cover	Provide contamination and acoustic protection for launch. Open one time on-orbit, fail safe	Structure Design
Loads	Instrument: 13 G's one axis at a time	Charles Kim
Derived Requirement for FMA Reference Concept		**Source**
Structural obscuration of reflectors	~7.8% outer shells, 12.6%-13.5% inner,shells 90-103 completely blocked (not there)	Effective Area requirement
Structure CTE	Match Reflector CTE (6.3E-6/C) as close as possible. FMA Angular Resolution error term of 2 arc sec for thermal drift	Structure Design
Reflector to sub-module Housing alignment	3.00 arc-sec	Optical Performance Error Budgets
P to S Separation between mirrors (cap)	50mm	Reference Optical design
Maximum Shell ID	1608.96 mm	Reference Optical design
Reflector spacing (back of one mirror to front of next)	Range between 1.0364 mm and 4.3905 mm	Reference Optical design
Operating Temperature	20 +/- 1 degree C	Thermal Control
Temperature Gradient	+/- 1 degree C	Thermal Control
Constraint		
Reflector Length	<20 cm	Reflector Formation
Reflector Modulus of Elasticity	10.6 msi	Reflector Formation
Reflector Strength	16.8 ksi for D263 glass based on limited test data	Reflector Formation
Reflector CTE	6.3 E-6/C.	Reflector Formation
Reflector thickness	410 microns +/- 30 microns	Reflector Formation

FMA Reference Concept

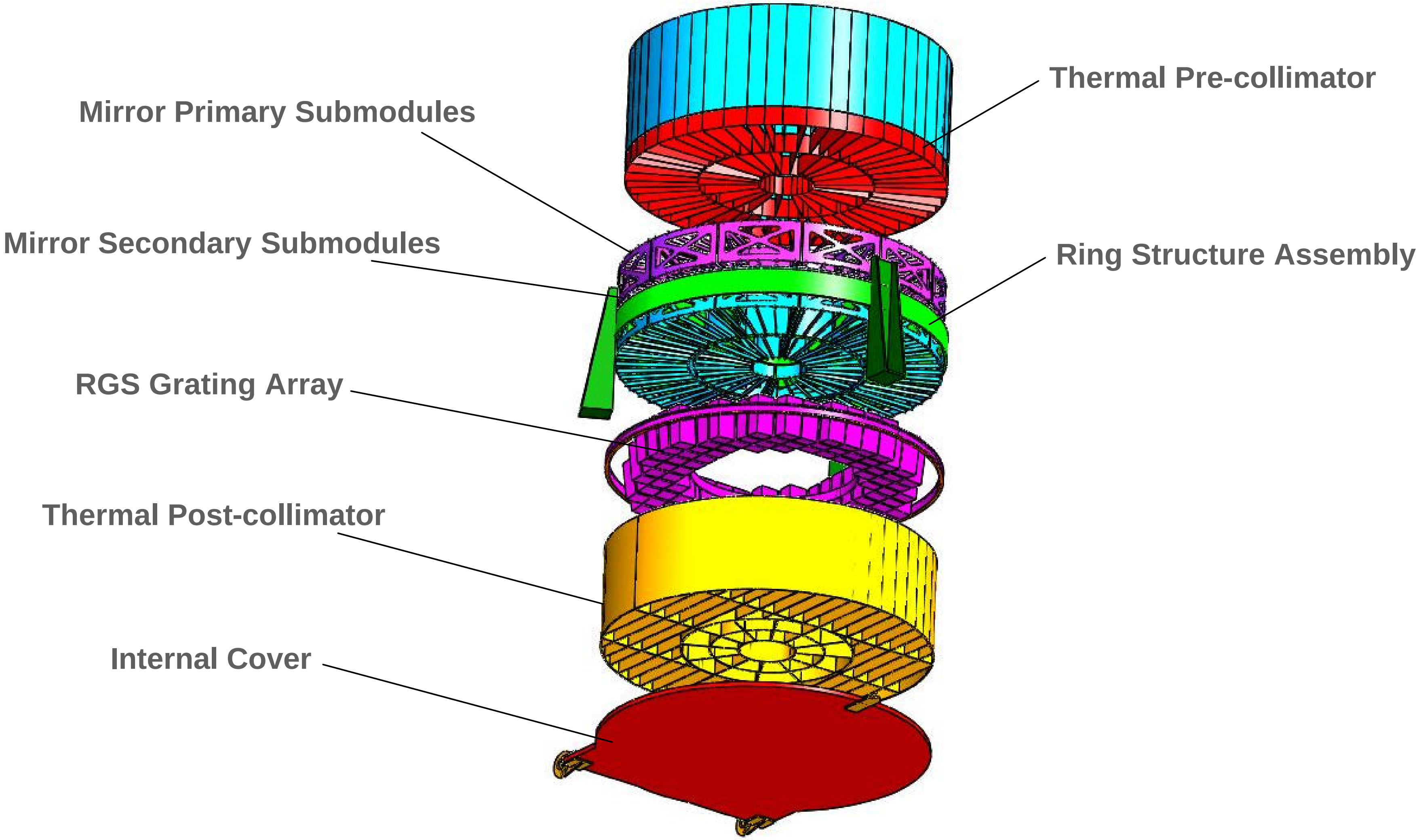
- **Mass Summary**

FMA Mass (kg)	Current Design
Module Structure	245
Reflectors	205
Pre collimator	31
Post collimator	16
RGA (Grating Modules & GIS)	75
Support Structure	153
Internal Cover	10
Inserts	5
Fasteners	5
Thermal Control	5
TOTAL MASS (kg)	**750**

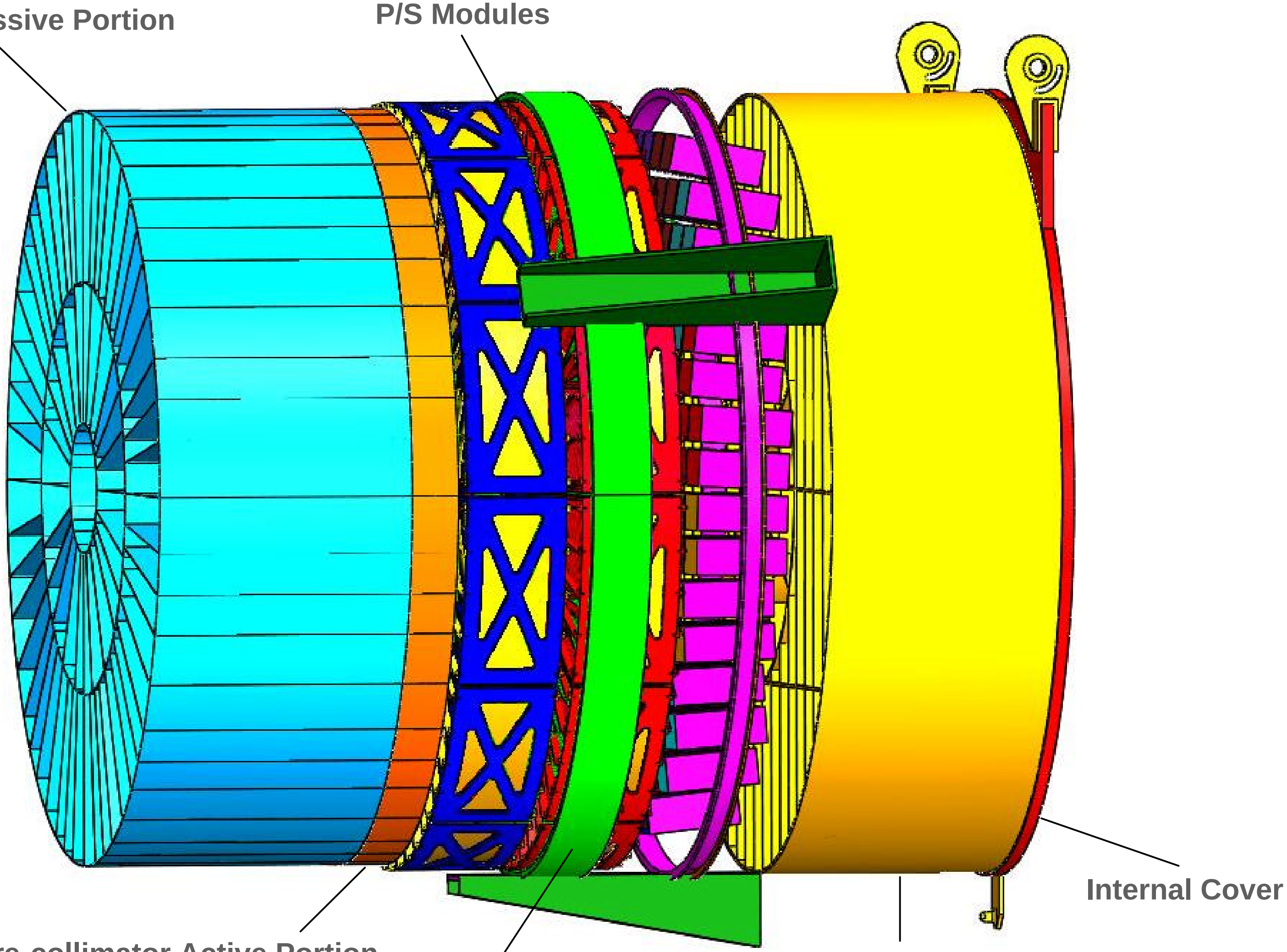
FMA Mechanical Design

FMA Reference Concept

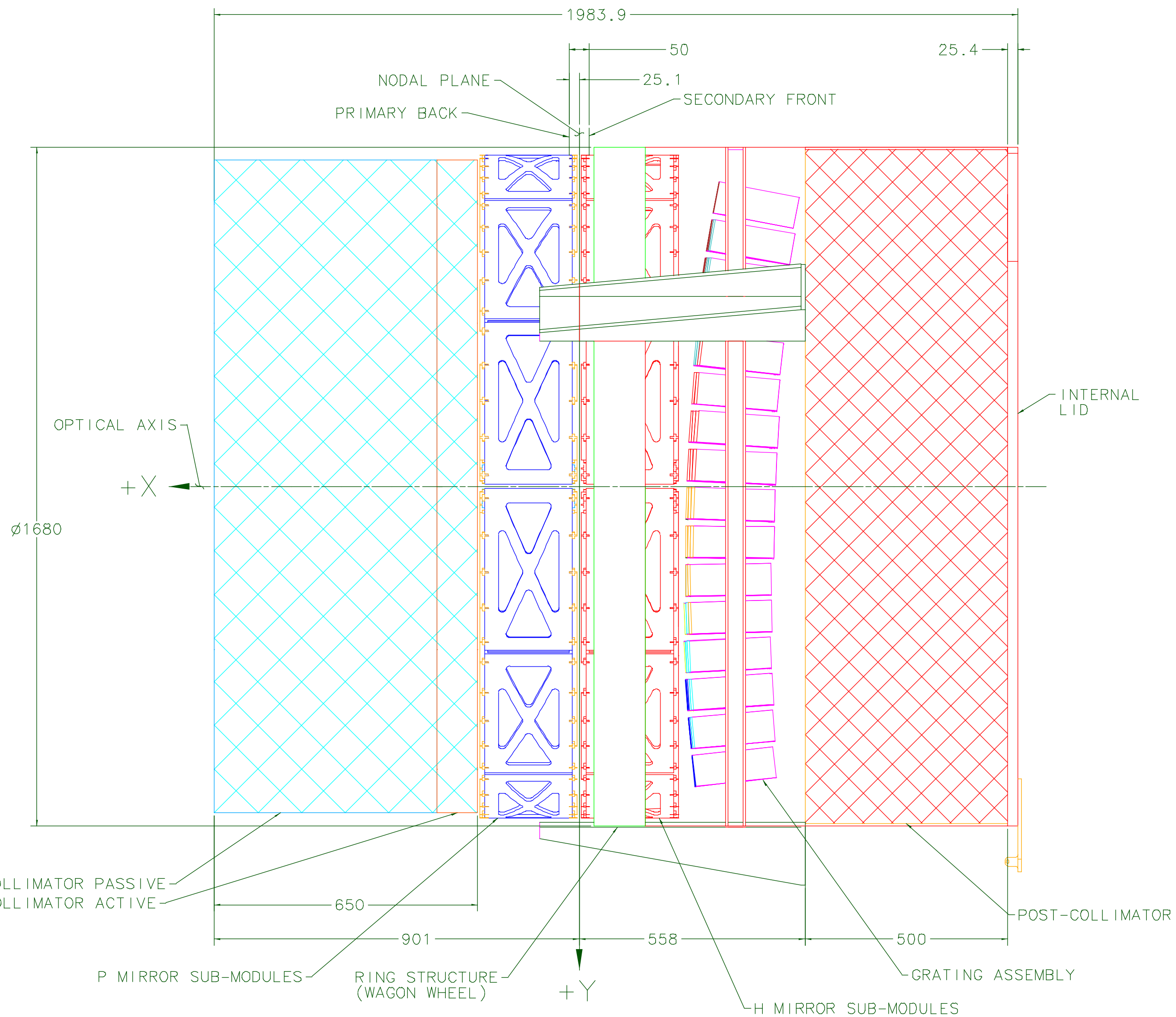
- 1.6M Diameter FMA Assembly



FMA Reference Concept (General)



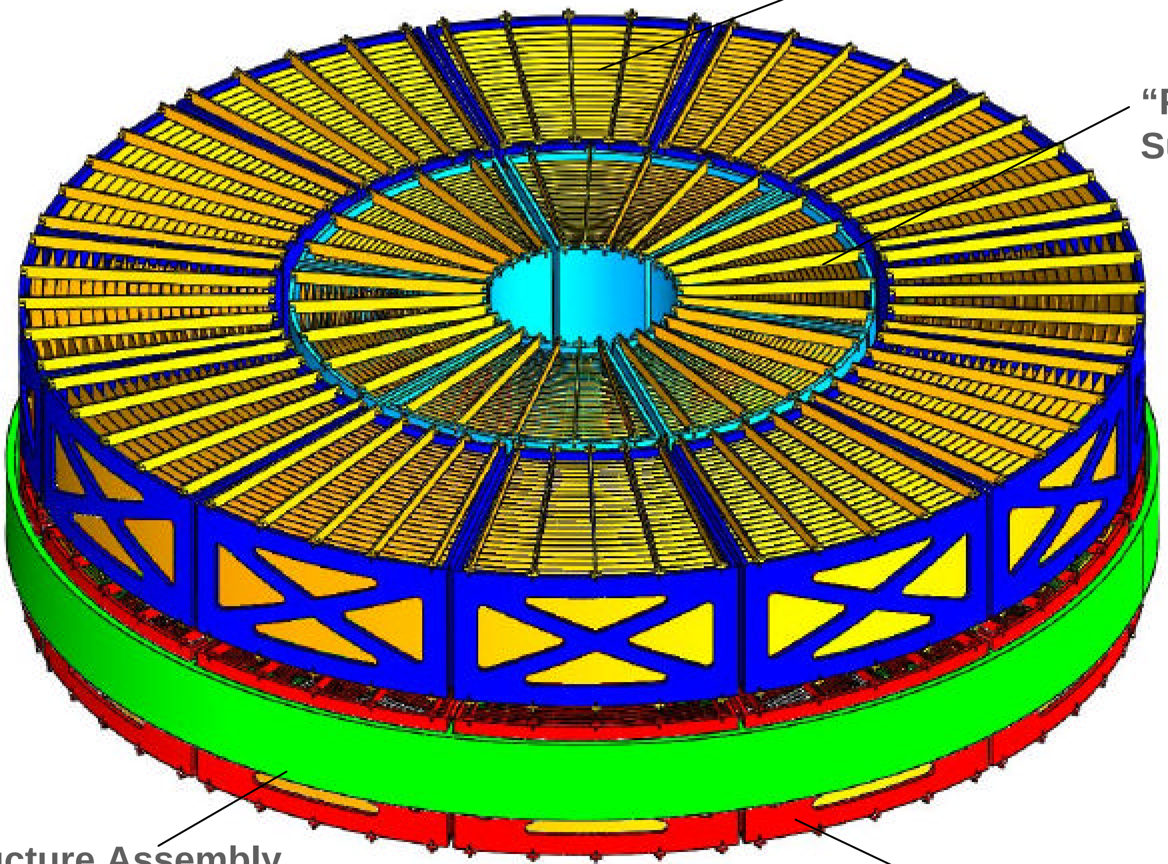
FMA Reference Concept



Dimensions are in mm

FMA Reference Concept

- General Overview of Design

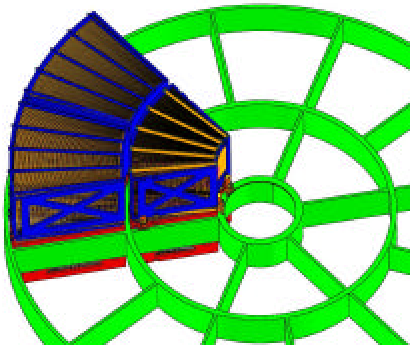


Reference FMA Design Concept

- Although there are 230 reflector diameters in the optical design, we needed structure to hold them.
- Placement of structure required us to remove 14 reflector diameters.
- Also wanted to optimize our strut design to use the same strut cross- section for both inner and outer modules.
- We divided the reflectors into inner and outer modules based on equivalent strut stresses resulting in:

	Reflector Diameter #s	Number of Reflectors Per Submodule
Inner Module	104 — 230	127
Outer Module	1 — 89	89

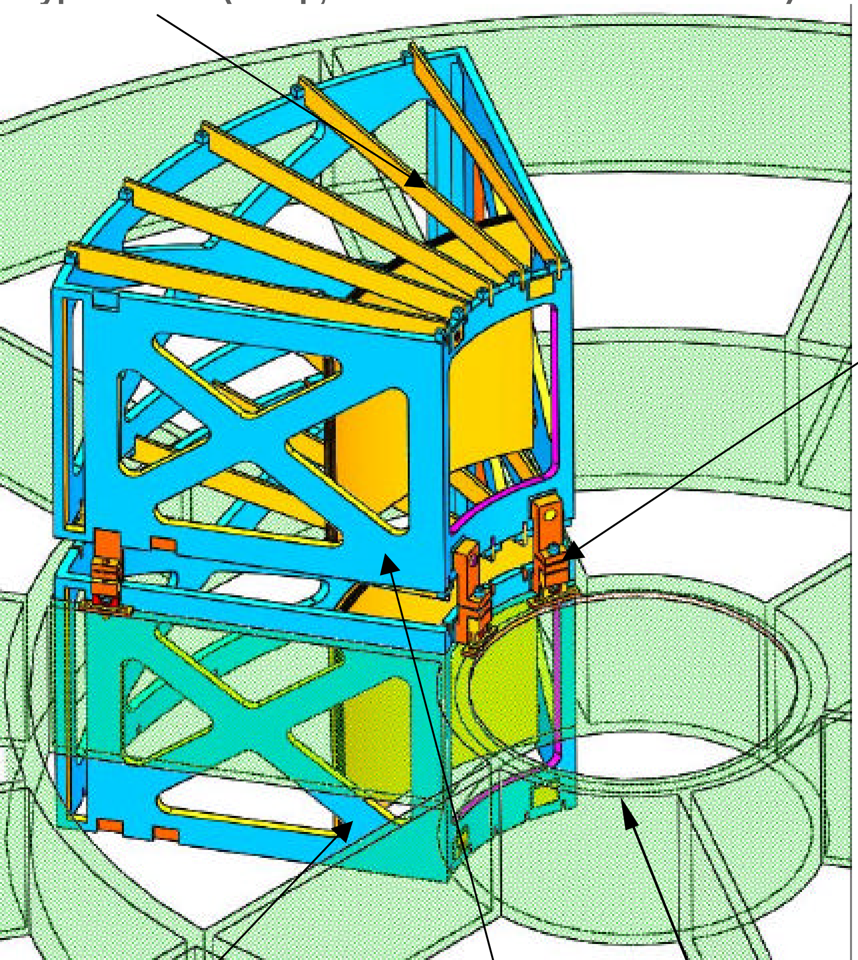
- Total Number of Reflector Diameters in Design: 216



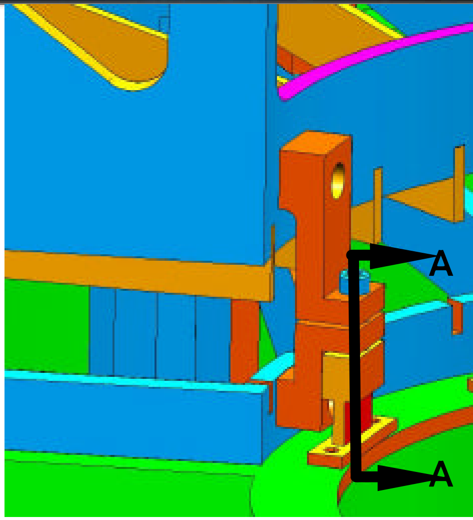
Reference FMA Concept

- **Typical P/S Module Stack up:**

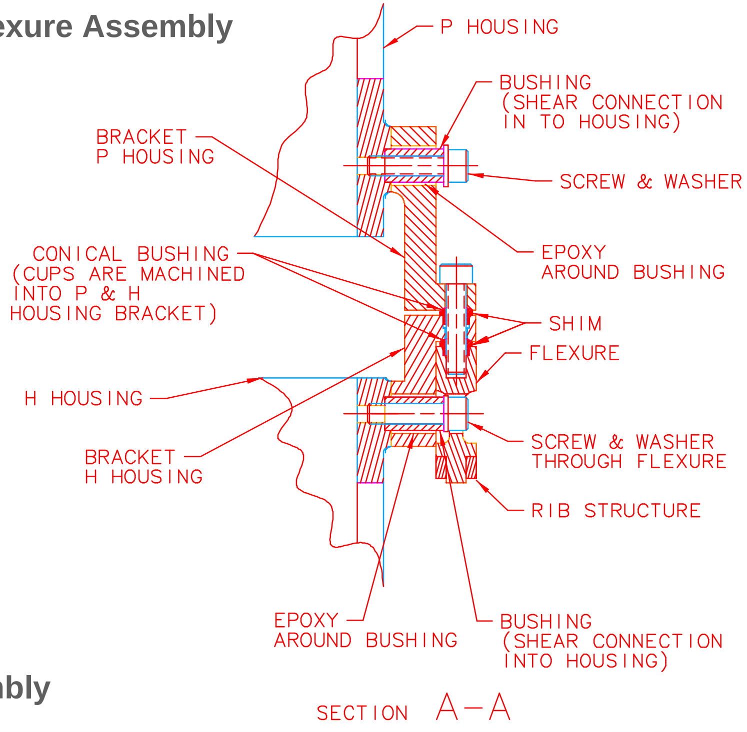
Typical Strut (5 Top, 5 bottom on each Submodule)



This concept uses flexures to attach the P and S sub-modules together, as well as, to the Ring Structure Assembly



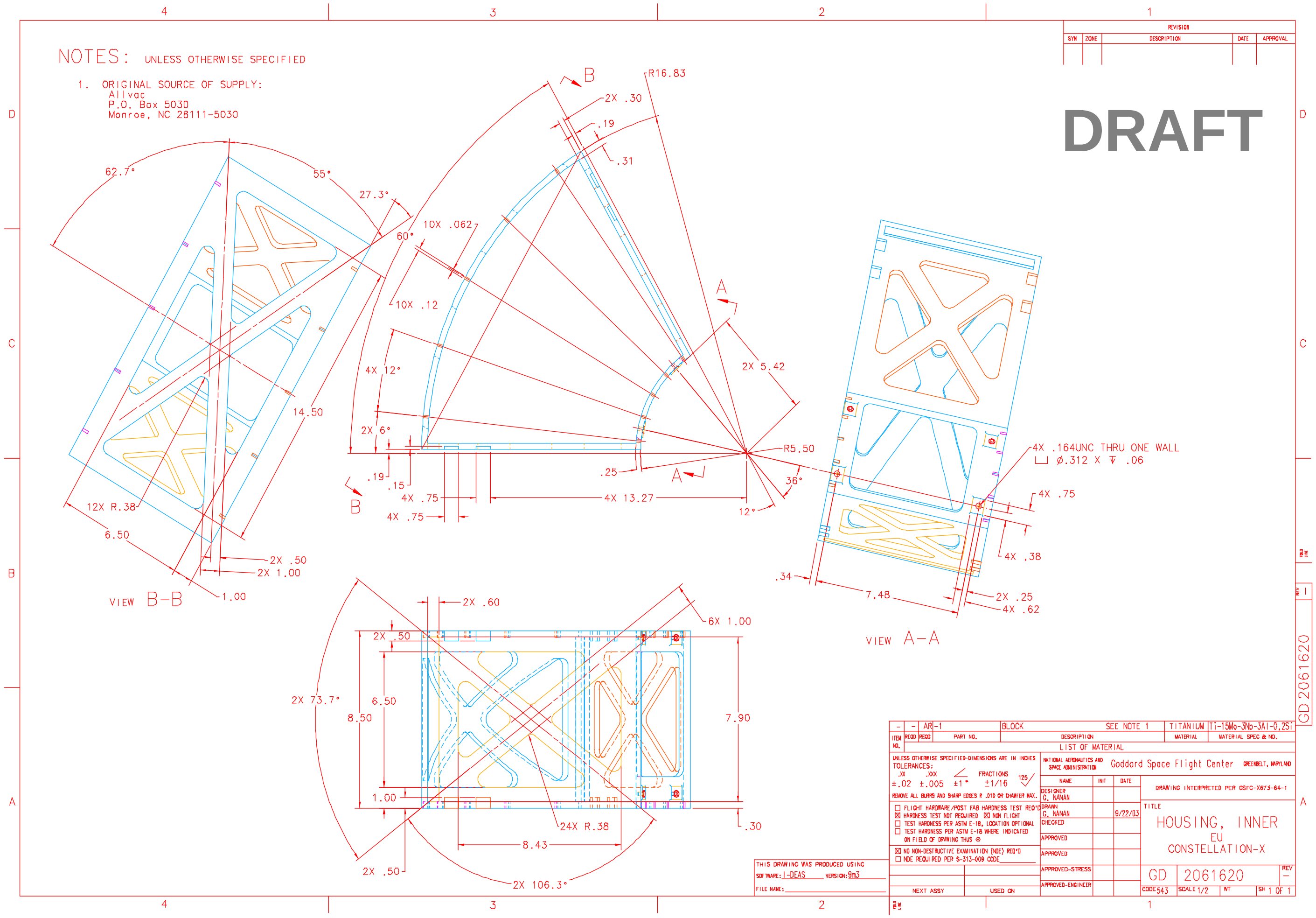
Typical Flexure Assembly
4 Places



S Submodule **P Submodule** **FMA Ring Structure Assembly (“Wagon Wheel”)**

Reference FMA Design

- **Submodule Housing Design (Fabrication Print):**



CTE of FMA Materials in Reference Concept

Material	Use	Coefficient of Thermal Expansion (10E-6 / C)
D263 Glass	Reflector	**6.3**
Ti-15Mo Titanium	Baseline Housing	6.1 to 6.8
Metal Matrix Composite: Beryllium/BeO Composite	Housing alternative material	6.3
UV Cure Adhesive	Quick Cure Adhesive between reflector/strut	
Stycast 2850 FT Catalyst 9	Baseline Structural Adhesive between reflector/strut	29.0 *
Hysol EA9394 Adhesive	Alternate Structural Adhesive	64.0 *
M55J/954-2A Composite	Ring Structure Assembly "Wagon wheel"	Near zero
*Note: CTE tested in GSFC Materials Lab		

-***Currently working with titanium for the EU housing because its easier to work with than Beryllium/BeO.***

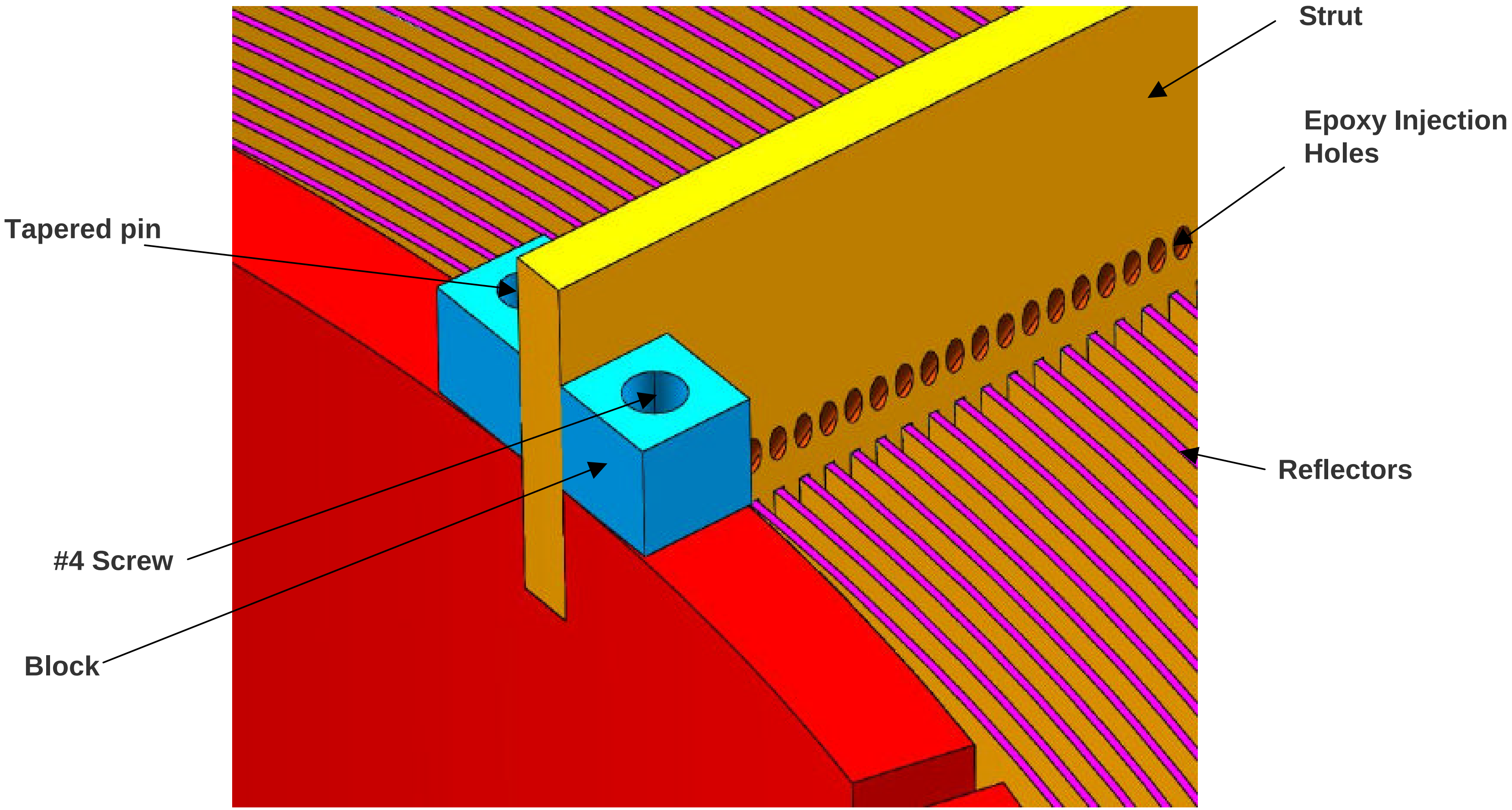
-***Regarding production, titanium is castable; Beryllium/BEO can be Hot Isostatically Pressed (HIP), so either is possible.***

-***Currently using a 5 minute epoxy to rapidly secure reflector to the strut once aligned. Want to use UV cure for flight.***

-***Structural adhesive is applied after the 5 minute epoxy.***

Strut Concept

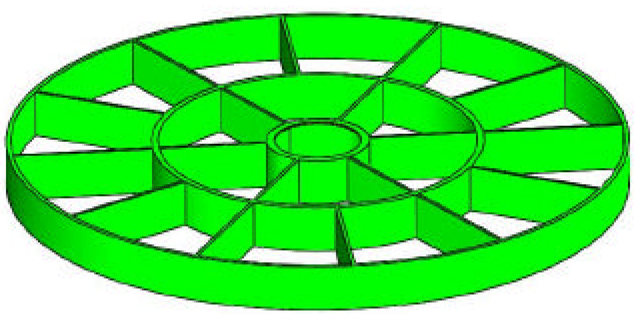
- Strut (With Grooves)



The strut will be glued to the block. The block will be matched drilled to the housing.A tapered pin is used for repeatability. This approach will allow us to recover faster if a mirror is broken during integration.

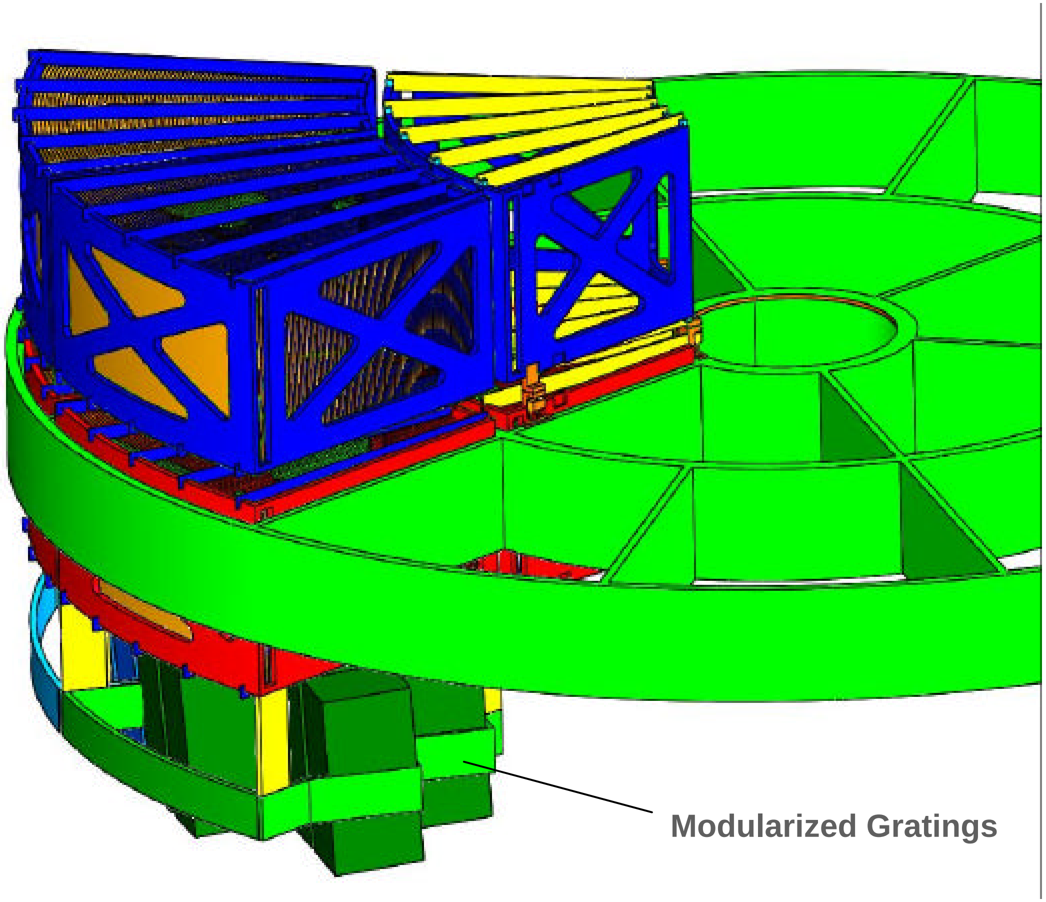
FMA Reference Concept

- Ring Structure Assembly (Wagonwheel) Materials in FEM Design:
  - M55J Honeycomb Outer Ring and Inner Ring.
    - Honeycomb increases the bending stiffness.
    - Lightweight.
    - Not limited by thickness as are spokes and middle ring.
    - Low CTE.
      - Flexures between rings and modules.
      - Can investigate other possible composite laminates with CTE closer to Glass.
    - Laminate middle ring due to space limitations.
    - Best overall Stiffness to Weight Ratio.
  - Spokes
    - M55J Laminate (no core).
  - Middle Ring
    - M55J Laminate (no core).
  - M55J Laminate has Modulus of Elasticity close to Titanium.



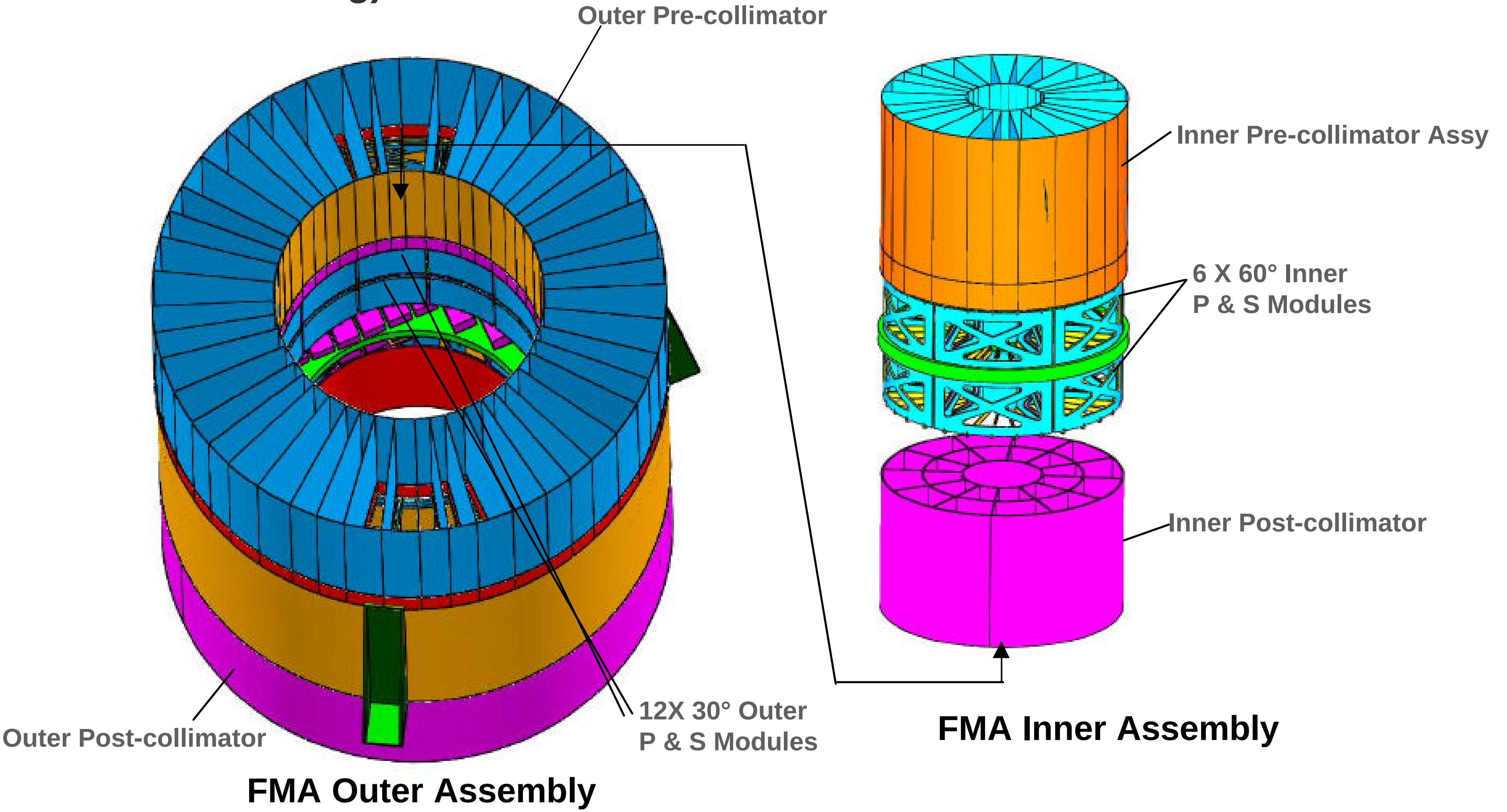
Reference FMA Design

- Modular Gratings, Modules and Ring Structure Assembly



FMA Design Option

- Separate Inner and Outer Rings (6 modules in inner ring; 12 modules in outer ring)



FMA Structural Analysis

This analysis is preliminary and will be reassessed before final requirements are defined for SOW release.

Structural Status for FMA Reference Concept

- FMA Structural Assumed Requirements
  - Instrument Interface Limit Loads → 13 G's
    - One axis at a time
  - Instrument Stiffness Requirement
    - Fixed Based Frequency > 50 Hz
  - All Structural Margins of Safety > 0.0
  - Material Allowables shall comply with the following requirements:
    - Metallic Materials: use "A" Basis Allowables
    - Nonmetallic Materials: use "B" Basis Allowables
    - All allowable/capabilities should consider the effect of temperature, fatigue, material nonlinearities, stability (buckling)
  - Thermal Environment
    - Operating Environment: 20 +/- 1°C

Structural Status

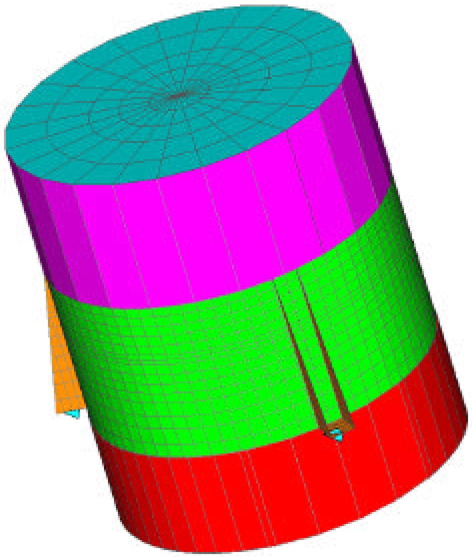
- Design Factors of Safety

Structure	Qualified by Test		Qualification * Test Factor	Acceptance or Proof * Test Factor	Qualified by Analysis Only	
	Yield	Ultimate			Yield	Ultimate
Metallic	1.25	1.4		1.2	2.0	2.6
Fastener and Preloaded Joints	1.2 (Joint Separation)	1.4		1.2		
Composites & Bonded Joints		1.5		1.2		
Glass (Nonpressurized)		3.0		1.2		5.0
Glass Bonds		2.0	1.4	1.2		

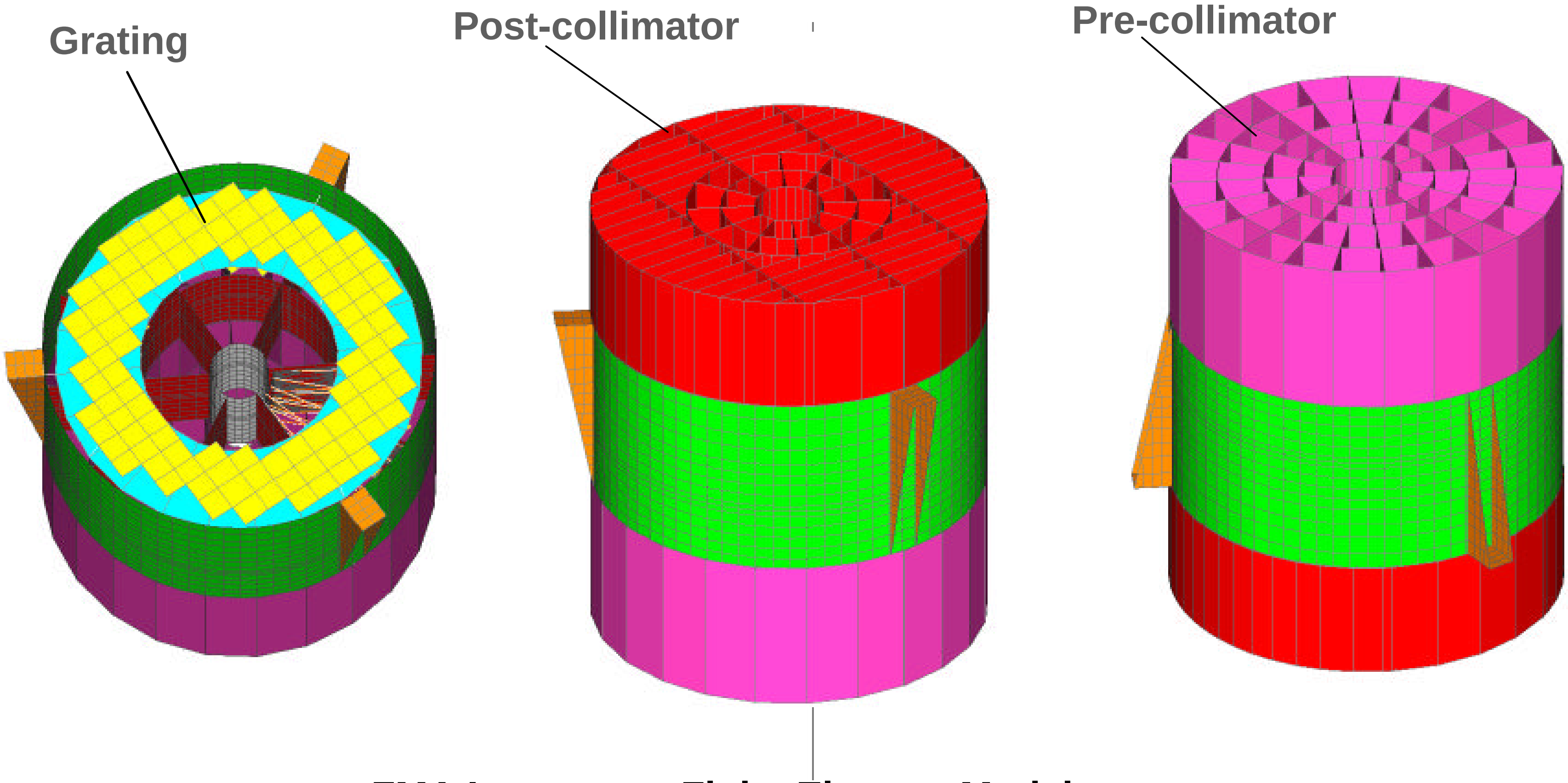
*Note: Qualification Tests are performed on flight-like hardware, while Acceptance or Proof Tests are performed on actual flight hardware.

Structural Analysis

- **Current Model Description**
  - Super-element Model
  - Mirrors have correct optical geometry
  - Number of Nodes: 73,526
  - Number of Elements: 66,749
  - Composite FMA Structure
  - Titanium Inner and Outer P-H Modules
    - Struts are also Titanium
  - Mass Models for Pre Collimator, Post Collimator, and Grating
  - Constrained in 3 translational degrees of freedom at spacecraft interface (3 locations)



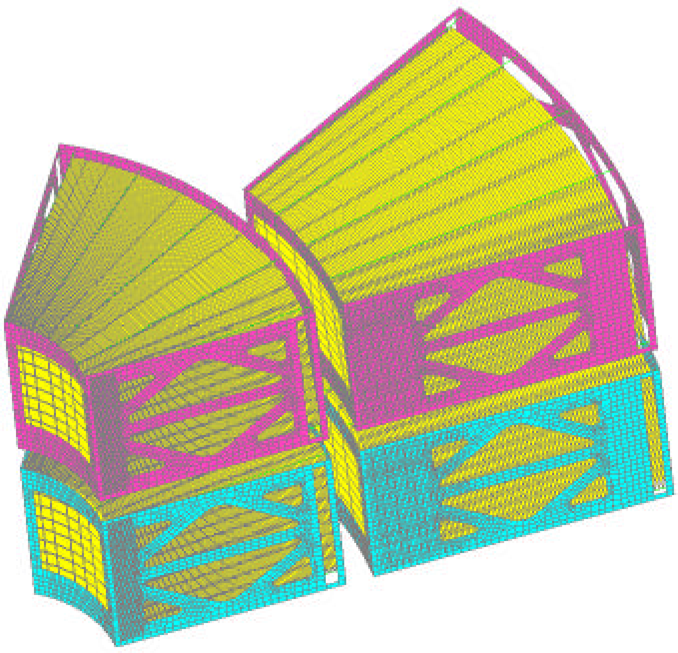
Structural Analysis



FMA Instrument Finite Element Model

Structural Analysis

- **Super-elements**
  - One inner module and one outer module are modeled in detail and are primary super-elements
  - All other modules are defined as identical image super-elements and are not separately modeled.
  - This approach allows us to have structural detail while keeping the size of the model at a manageable level
  - Model would be 540,000 elements rather than 67,000 elements if super-elements were not used

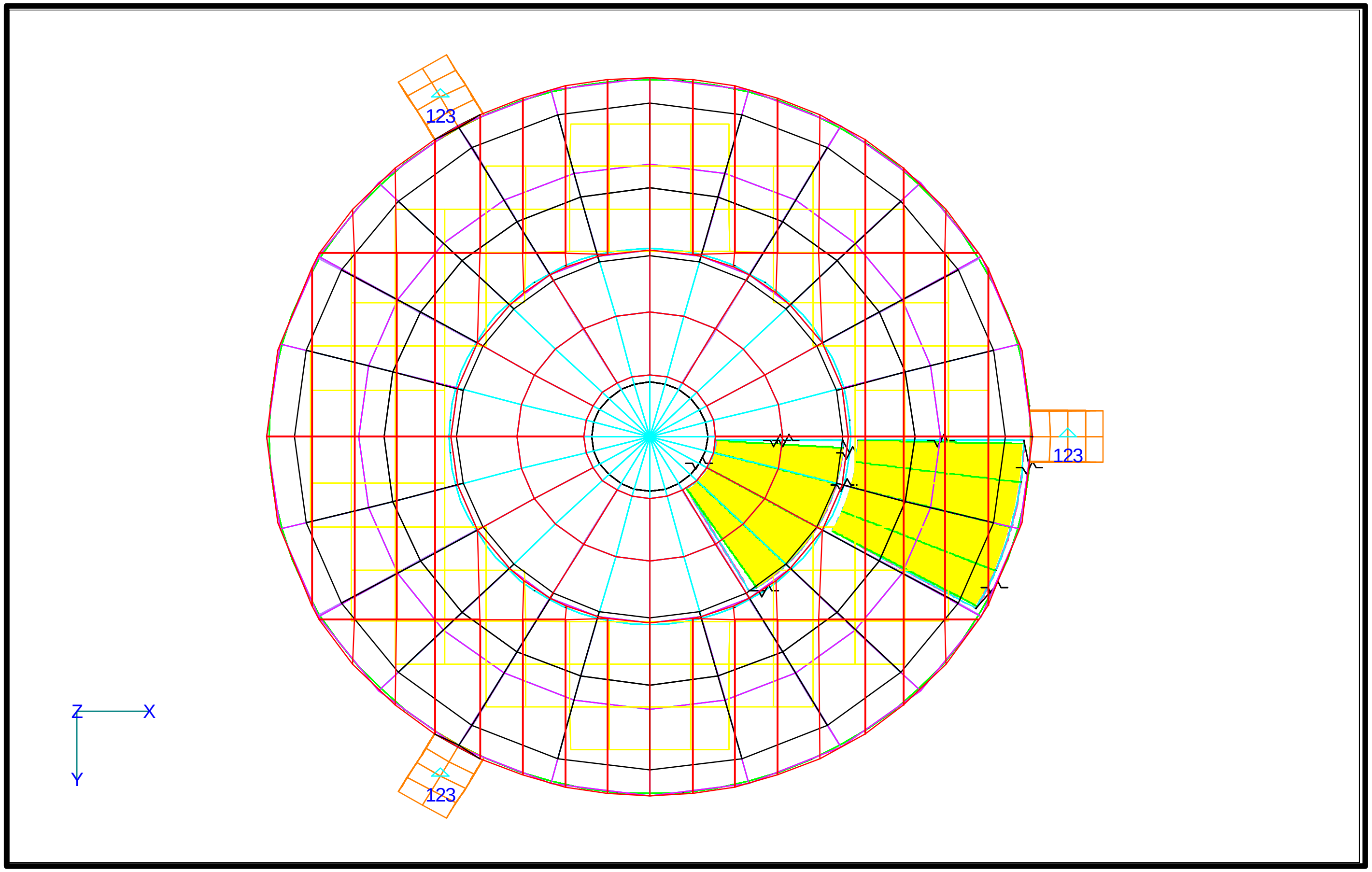


FEM of P and S Modules with Mirrors

Structural Status

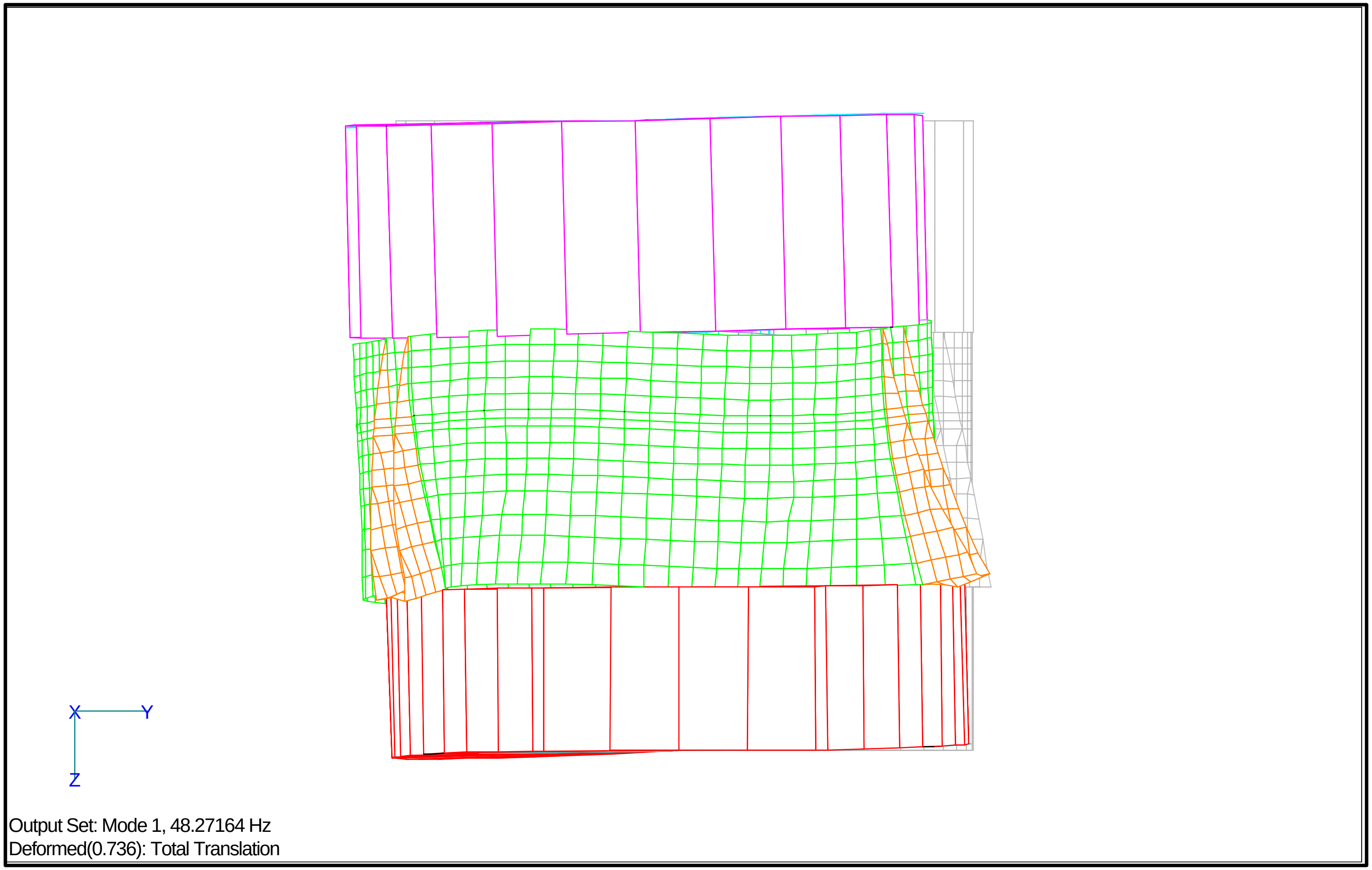
- Mirror Details
  - D263 Glass (Thickness = 400 microns)
  - Non-structural mass put on elements to represent Epotek epoxy and gold material
- Large Stress Gradients at Constraints → Therefore, refined model at maximum stress constraint location
  - Modeled Stycast Adhesive.
    - 5 mil bondline assumed.
  - Section of Titanium Strut in Model
- Loads
  - Reference GEVS – SE Rev A, June 1996

Structural Analysis



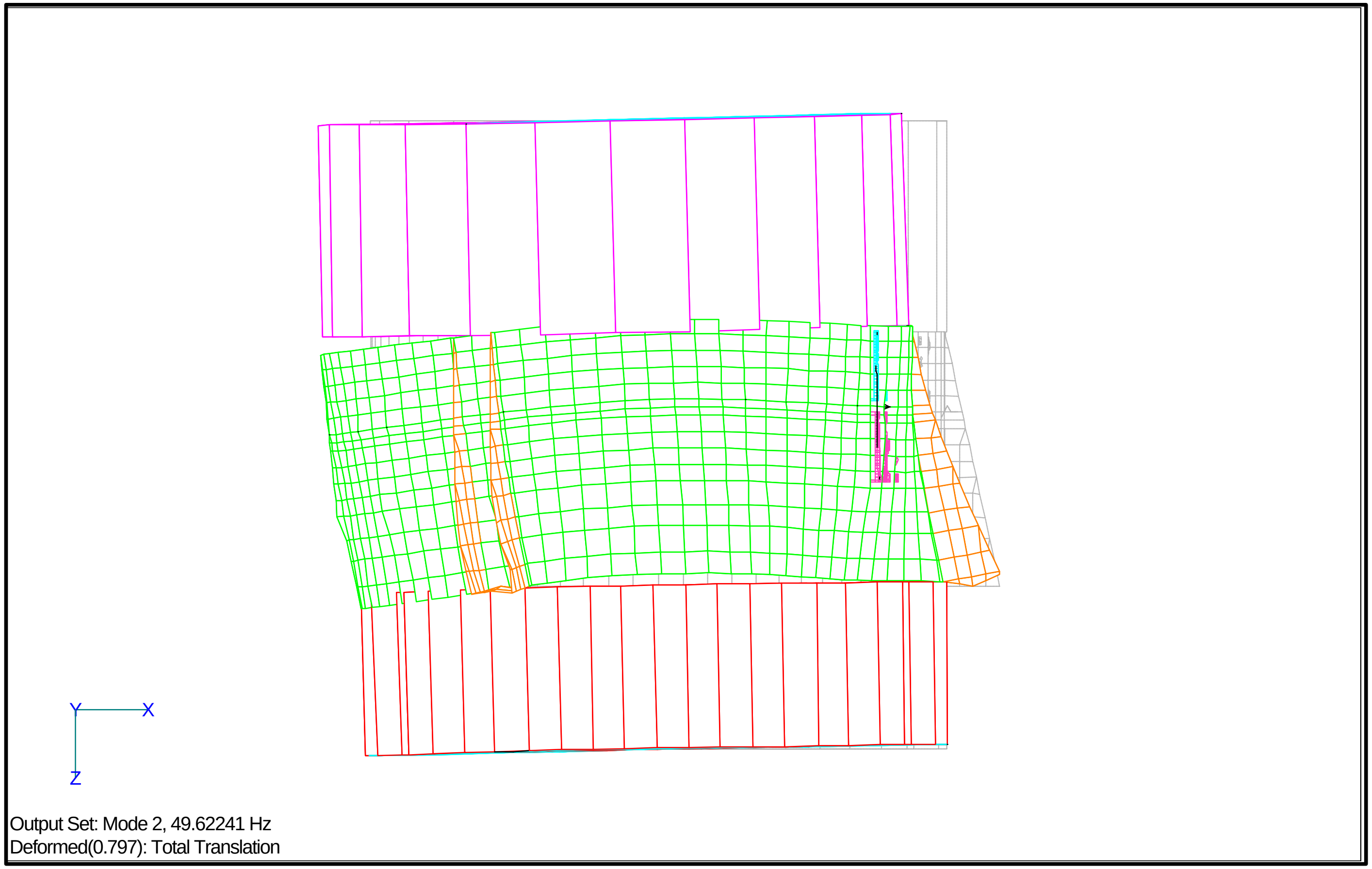
FMA Instrument Finite Element Model

Structural Analysis



Mode Shape: Translation in Lateral Direction
Fundamental Frequency: 48 Hz
Current Preliminary Design: Small Design Modifications (I.e., weight savings initiatives) will easily achieve 50 Hz.

Structural Analysis



Mode Shape: Translation in Lateral Direction
2nd Mode: 50 Hz

Structural Status

- Reflector Material Properties:
  - E 10.6 msi
  - CTE @ 20C 6.3 ppm/C
  - Thermal Conductivity 0.0462 btu/hr-in-f
  - Density 0.09 lb/in^3
  - Poisson's Ratio 0.208
  - Mirror tensile Allowable 16.8 ksi *

* This value (16.8 ksi) was obtained from very limited test data on formed substrates.

Structural Status

- **How good is our stress allowable number for reflectors**
  - **Glass Strength is dependent on many factors**
    - **Tensile Failures Occur by Propagation of Existing Fractures**
    - **Processing – Slumping, Annealing, Edge Cut Conditions, Surface Conditions**
    - **Thickness**
  - **Strength Tests were performed in 1999**
    - **D-263 0.3mm, 0.4mm, and 0.9mm**
    - **Strength Varies With Thickness – Thicker Glass has Higher Strength**
    - **Slumping of 0.4 mm Samples Reduced Strength by ~50%**
    - **Large Scatter in Strength Data**
    - **Minimum Tested Strength of 0.4 mm Slumped Glass is 16.8 ksi**
  - **Further Testing is underway**
    - **Additional Tests of Slumped Samples**
    - **OAP-2 Vibration Tests to Failure**

Structural Status

For Information Only (not a requirement):

A conservative snapshot of where we are…

Preliminary Random Vibration Qualification Test Levels from GEVS for Instruments Weighing Over 182 kg (400 lb).	
Frequency	**ASD Level**
(Hz)	(G^2/Hz)
20	0.01
20-50	+2.28 dB/oct
50-800	0.02
800-2000	-2.28 dB/oct
2000	0.01
Overall	**5.65 Grms**
Existing Instrument Design	
Preliminary 1 Sigma Random Vibration Load Normal to Mirror in Existing Instrument Design derived from GEVS input levels applied to base of instrument model.	11.7 G's

Structural Status

- Plans for the Future
  - Investigate ways to reduce loads:
    - Isolation mounts (launch locks).
    - Increase damping in the structure.
  - Complete Material Testing for Glass
  - Evaluate other Reflector Materials to augment D-263
  - Continue Random Vibration Analysis
  - Perform Vibro-Acoustic Analysis
  - Adhesive Selection for Reflector Mounting
  - Improve fidelity of Reference FMA model.
  - Look into optimizing FMA to decrease weight.
  - Model our structure kinematic mounts to optic module to the spacecraft. Attach points to the FMA.

Constellation X
The Constellation X-ray Mission

Grating Accommodation Requirements and Concepts

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RGS IPT Lead
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Outline

- Overview
- Reference Concept
  - RGS Overview
  - Reference Grating Concept
  - Grating Flow-down Requirements
  - Grating Geometry
  - Modules: Approach, concept, layout, orientation
- Requirements and Constraints
  - Overview and coordinate system
  - Alignment requirements
  - Thermal, mass and mechanical requirements and constraints
- Reference Documents
- Summary

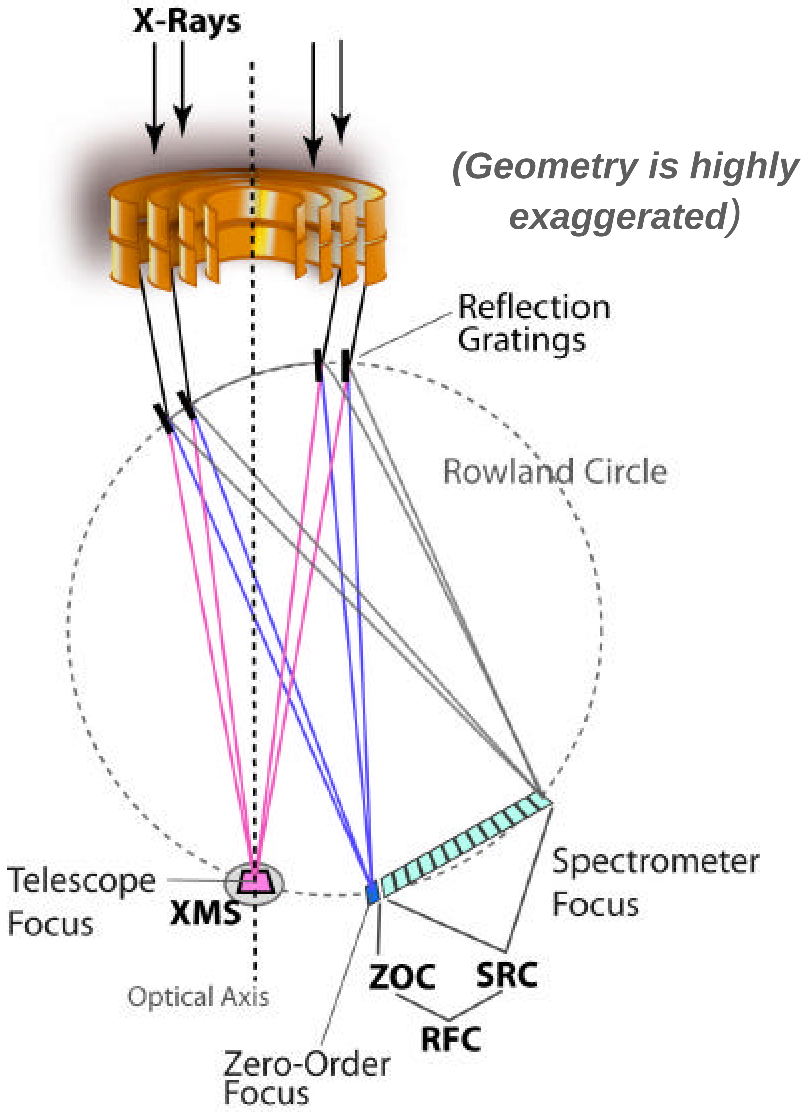
Reflection Grating Spectrometer Overview

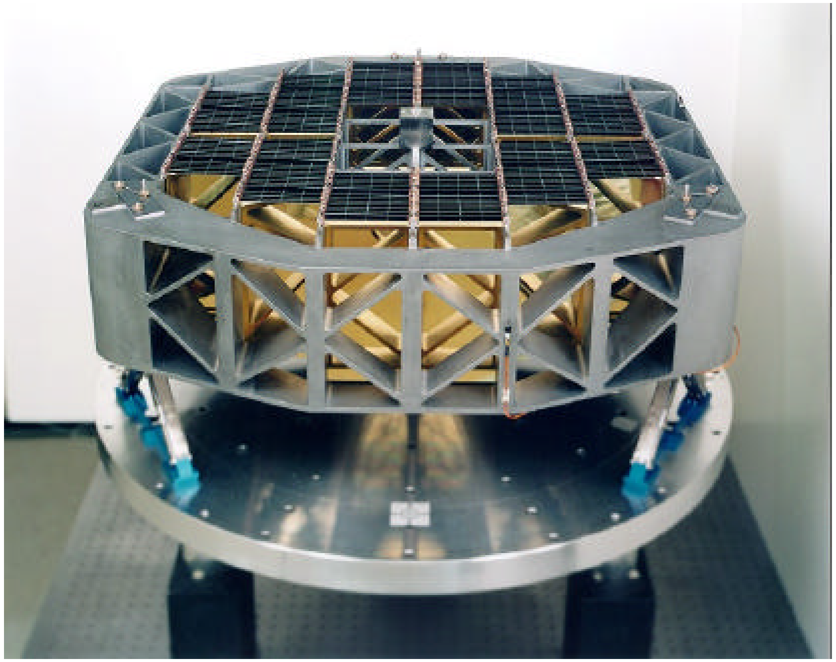
- The Reflection Grating Spectrometer (RGS) is an array of co-aligned reflection gratings (RGA) which reflect and disperse X-rays to the RGS Focal Plane Camera (RFC), an array of back-illuminated CCD detectors.
- RGA consists of ~1000 individual gratings held at grazing incidence with respect to the local converging beam. The RGA focuses the X-rays onto the RFC in an inverted Rowland design.
- The RFC uses two camera systems: the zero-order camera (ZOC) and the Spectroscopy Readout Camera (SRC).
- The SRC images the dispersed spectrum while the ZOC reads out the reflected image; it anchors the wavelength scale by tracking small aspect drifts.
- The RGA uses a modular approach: ~10 identical gratings are aligned and assembled into grating modules. These identical modules are attached to the Grating Integrating Structure (GIS).
- The RGS system performance requirements trace to top level mission requirements. Spectral resolution is driven by SXT mirror angular resolution.

RGS Performance Requirements

RGS Performance Requirements	Trace to Mission Top-Level Requirements	RGS Performance Requirements
Bandpass	0.25-2.0 keV (6 to 50 Å)	Bandpass
Spectral resolving power, R ($E/\Delta E$)	$\geq$300 below 1 keV	Spectral resolving power, R ($E/\Delta E$)
Effective Area: @0.25 keV @0.6 keV @1.25 keV	 250 cm^2 625 cm^2 175 cm^2	Effective Area: @0.25 keV @0.6 keV @1.25 keV

RGS Schematic: RGA+RFC

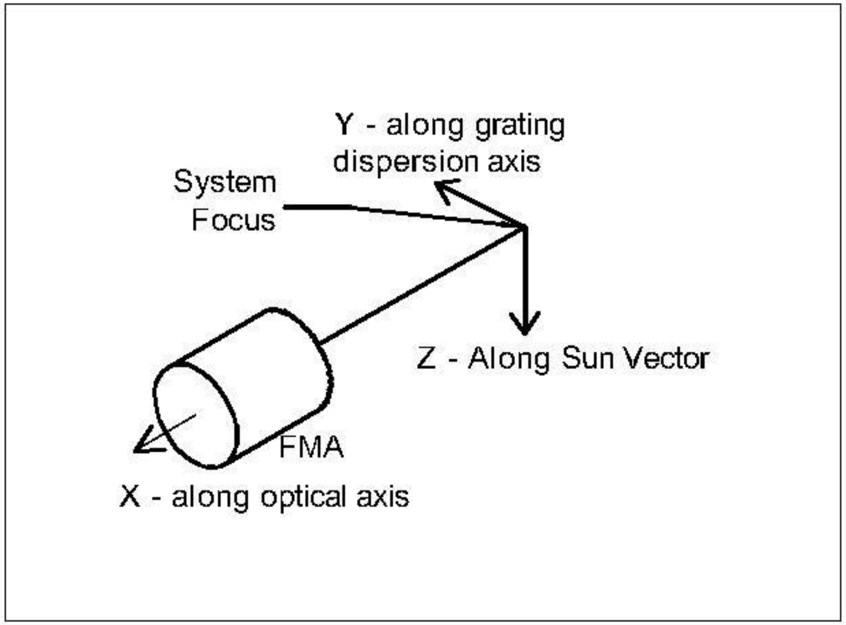




- **XMM-Newton RGS (above):**
  - **182 gratings (100x200mm) for each of 2 arrays**
- **Constellation-X RGS:**
  - **~1000 gratings (100x200mm) per FMA**

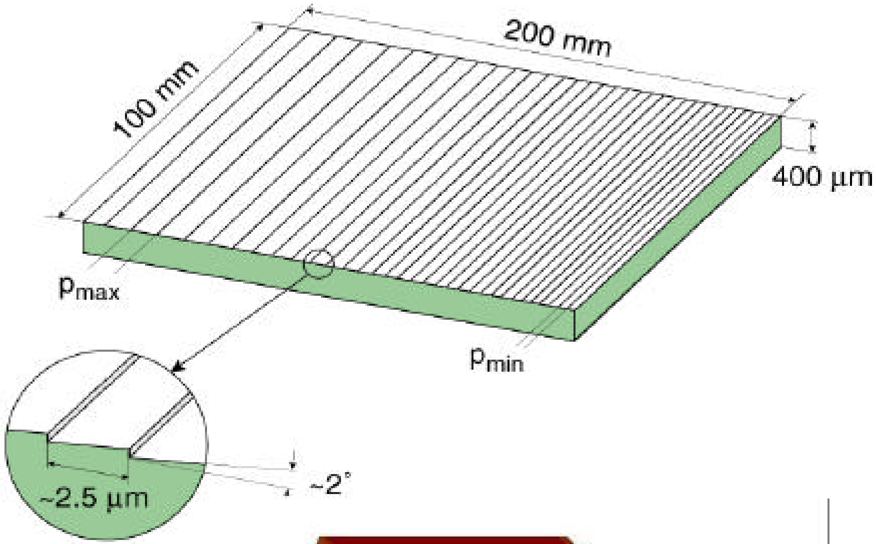
FMA Coordinate System (used for Grating Alignment)

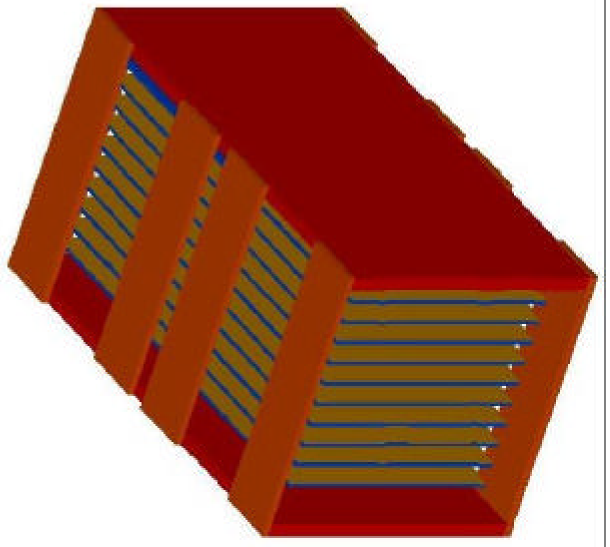
- Origin is at the FMA nominal (design) focus
- X axis is along optical axis, positive from the focus to the FMA
- Y is along the nominal dispersion axis
- Z is orthogonal to X and Y and nominally aligned with the sun vector for zero roll and pitch
- FMA mid-plane is nominally 10,000mm in +X direction from origin



Reference Grating Concept

- **Substrates**
  - Silicon or glass sheets, 100x200 mm
  - Thickness 0.4-1.0 mm, flatness = 2 arcsec
- **Gratings (~1000/array, identical)**
  - Patterned on substrates
  - Period is 2.5 microns (407 l/mm)
  - Grating has 5% period variation (chirp)
  - Groove blaze = 0.6º, roughness = 0.5 nm
- **Modules (~100/array, identical)**
  - Hold ~10 gratings in fan-out configuration
  - Assembly alignment accuracy = 2 arcsec
  - Frame CTE matched to gratings (assuming $8x10^{-6}$ / ^{o}C for BK7 glass)



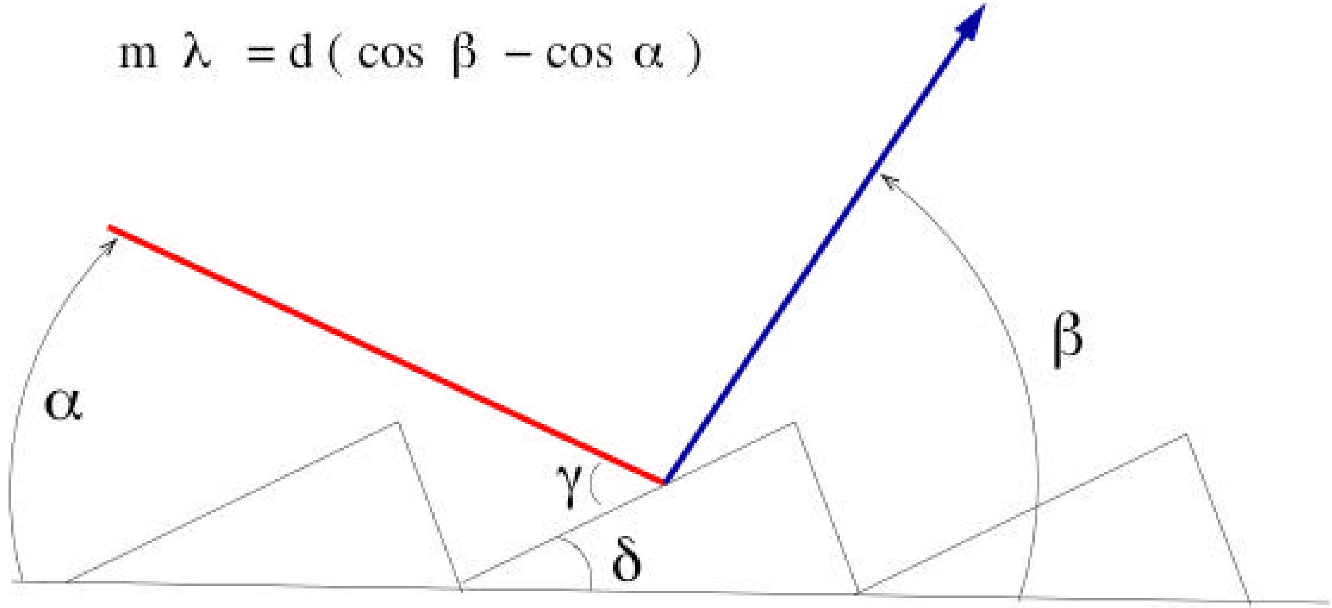


Grating Flow-down Requirements (for reference only)

Derived RGS Grating Requirements		Derivation
Grating efficiency: @0.25 keV (1st Order) @0.6 keV (1st Order) @1.25 keV (2nd Order)	 >0.14 >0.22 >0.06	Flowdown from area requirements. Theoretical efficiency with 50% margin. Met with 40% margin when measured efficiencies for anisotropically etched grating test ruling are used
Interception factor	0.57 to 0.6	Fraction of X-rays entering the clear aperture of modules intercepted by gratings and dispersed in the various orders. Flowdown from area requirements (energy dependent)
Straight-through factor	0.38 to 0.4	Fraction of X-rays entering the clear aperture of modules that is *not* intercepted by gratings; it propagates to the focus (energy dependent)
Grating groove parameters α: incidence angle γ: graze angle d: groove spacing	$\delta = 0.605$ deg. $\alpha = 1.61$ deg. $\gamma = 2.21$ deg. $1/d = 407$ mm^{-1}	Given 15 arcsec HPD telescope, and requiring $E/\Delta E = 400$ at blaze (grating blaze $\delta = 0.605$ deg.) reflectivity is optimized there using scalar diffraction theory.
Grating flatness	$\leq$2 arcsec FWHM	Grating error budget flowdown for spectral resolution. Combined with alignment error, allows broadening of the line spread function core by no more than 30% and SXT mirror dominates
Grating to grating alignment	$\leq$2 arcsec FWHM	See grating flatness item (above)
Mass	75 kg	Current engineering estimate for full RGA

Grating Parameters

$$m\lambda = d(\cos\beta - \cos\alpha)$$



$\alpha =$ angle of incidence w.r.t. grating plane = 1.61 deg

$\beta =$ diffraction angle w.r.t. grating plane

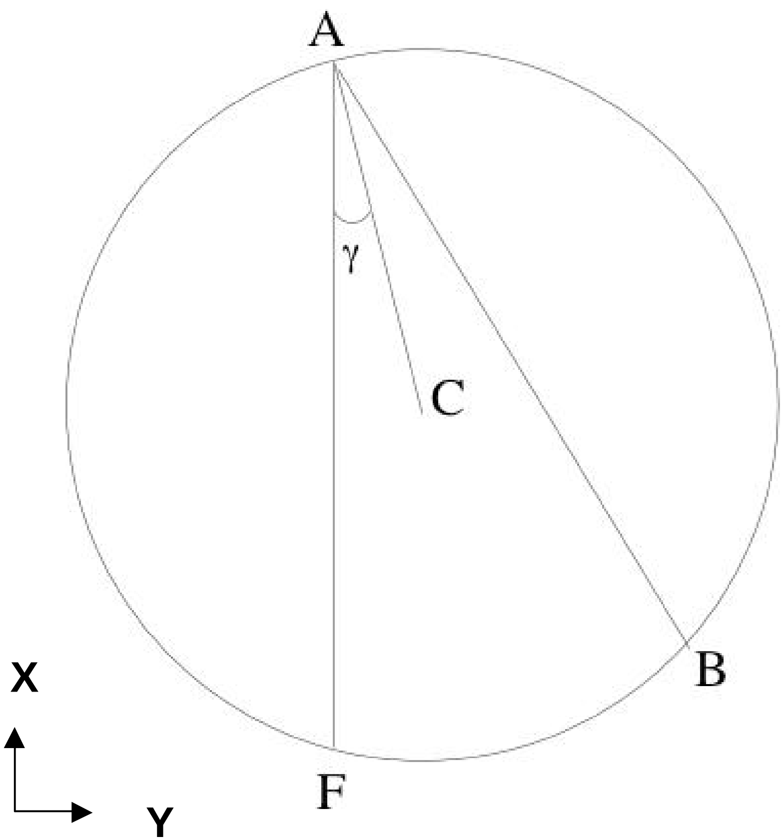
$\delta =$ blaze angle of facets = 0.605 deg

$\gamma =$ graze angle on facets = 2.21 deg

(1) $\alpha + \delta = \gamma$ (2) $\beta_{blaze} = \gamma + \delta$

Gratings are Aligned Along Rowland Circle in XY Plane

In XY plane defined by optical axis (X) and dispersion direction (Y), the Rowland Circle is defined by points A,F,B



F is SXT focus

A is center of a virtual grating placed on the optical axis, at axial center of grating module. Prime ray is at Angle of incidence a on the gratings.

AF is along optical axis

C is center of Rowland Circle; radius AC forms angle g with respect to AF

B, spectroscopic focus, forms isosceles triangle FAB

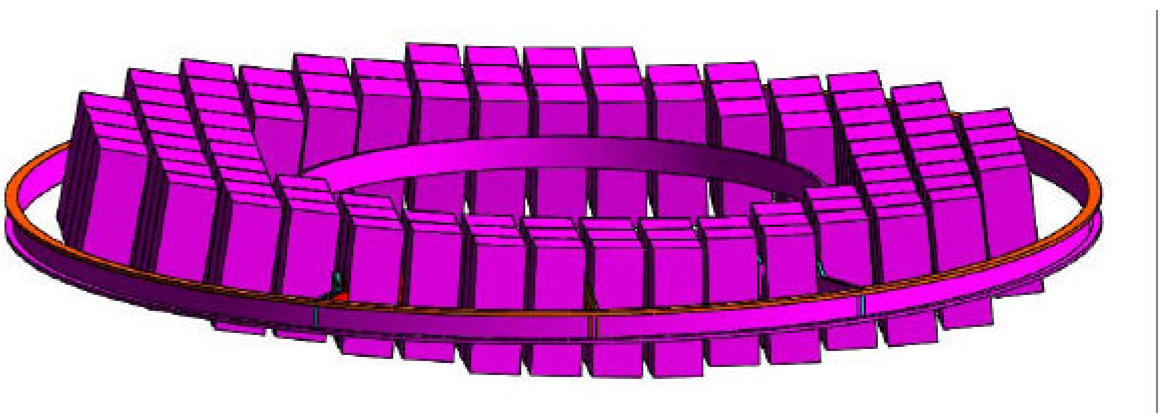
AF = AB = L
R = AC= L/(2cos(g))

Constrained values:

g = 2.21 degrees (TBR)
L = 9650 mm (TBR)

Arrangement of Modules above and below XY plane

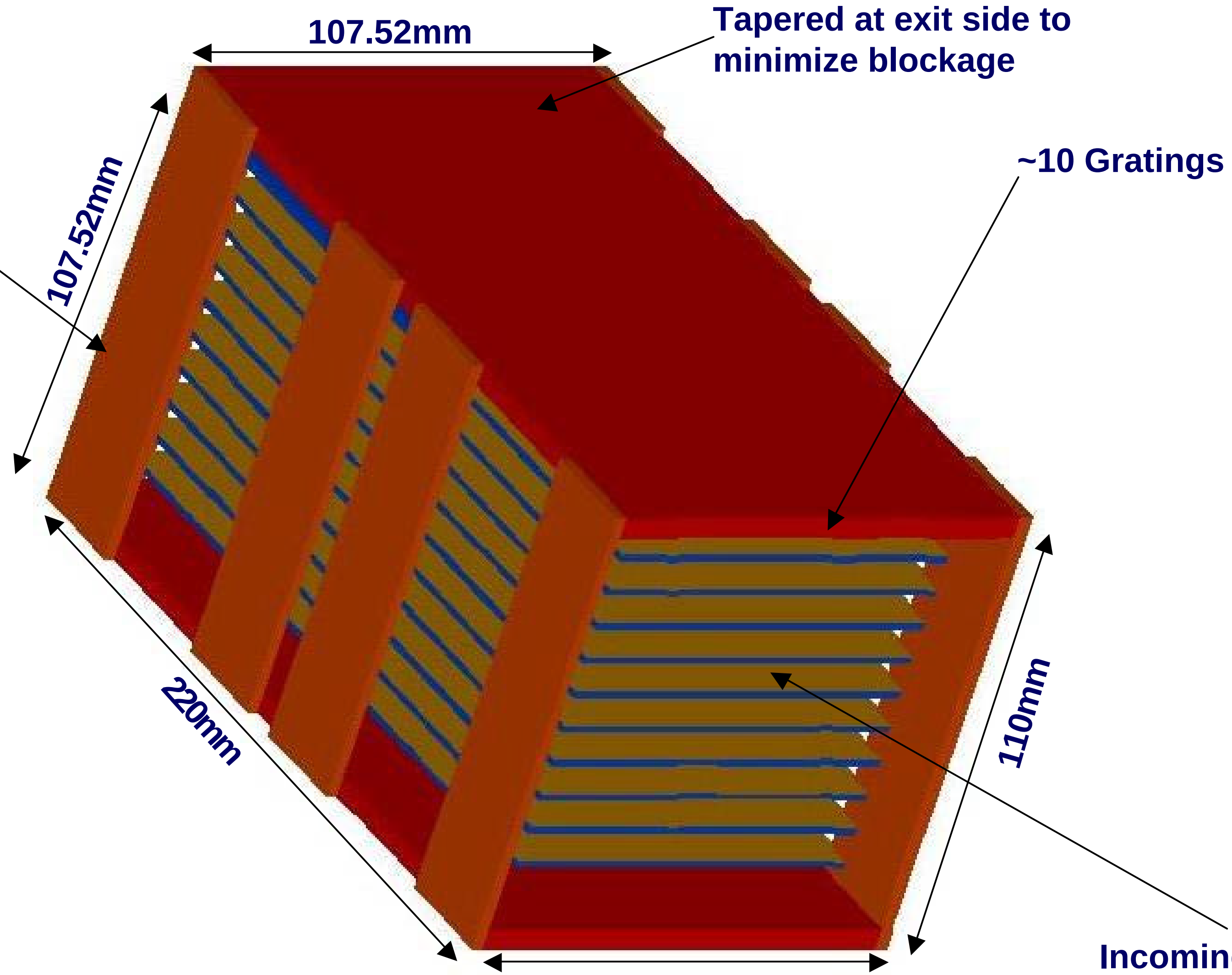
- The modules are not coplanar. They are arranged along a surface defined by rotating the Rowland Circle about an axis defined by chord FB



RGA Implementation – Modular Approach (Reference Concept)

- The RGA uses a modular approach (which was not employed in the RGS of XMM-Newton).
- Thin (<1 mm) gratings are assembled into modules. These modules are identical, and each contain ~10 identical gratings.
- The gratings are aligned within the module and bonded to the module frame. (Alignment satisfies grating-level tolerances.)
- The module is aligned within the grating integrating structure (GIS). (Alignment satisfies module-to-module tolerances, or ”differential tolerances”.)
- NOTE: The GIS is not constrained to be monolithic, as in the Reference Concept. Grating modules might be assembled into one or more structures which are pre-attached to the FMA.

Grating Module



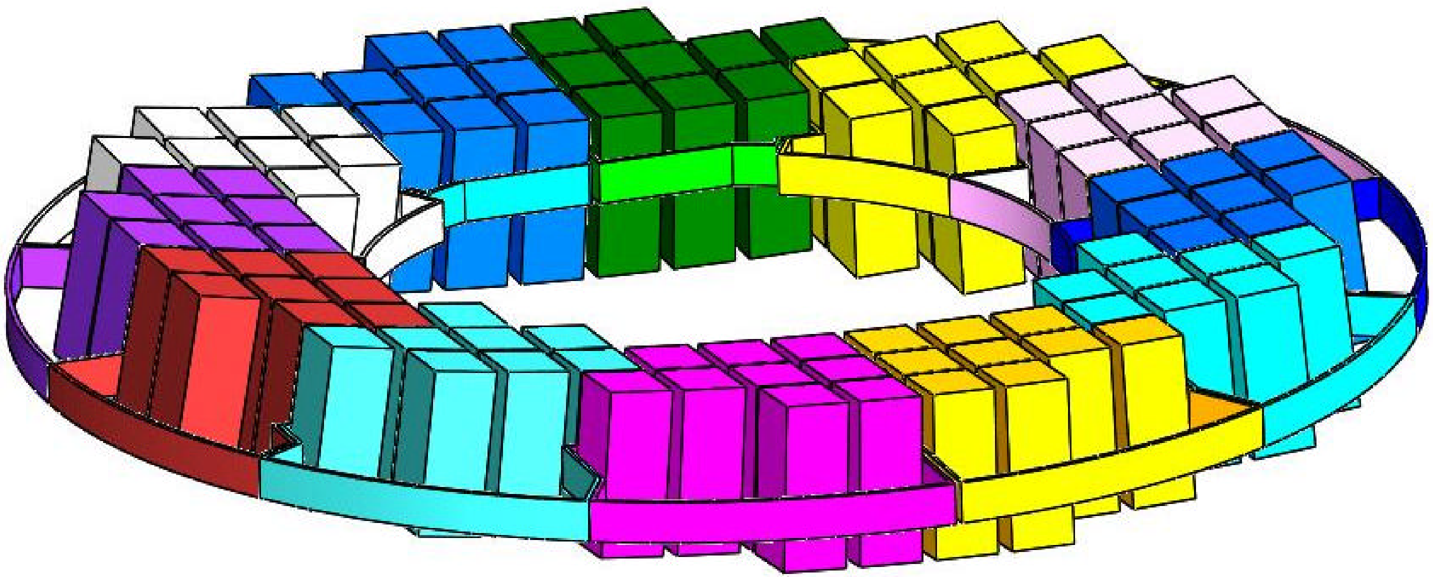
Grating size:
100mm x 200mm

Typical mass 520g

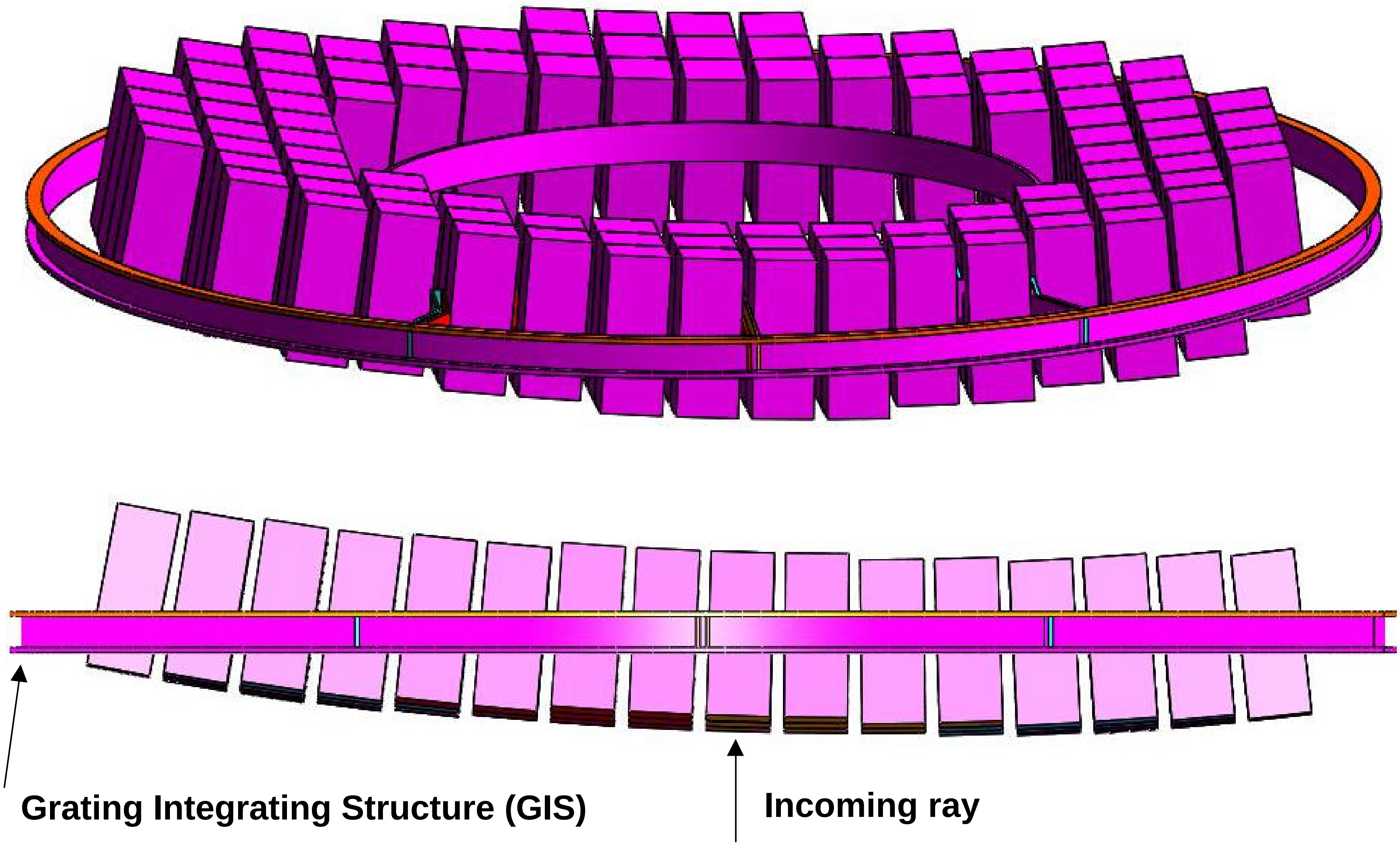
Constraint: 100 modules with these dimensions

Grating Module Layout (Reference Concept)

- Modules (100) partially cover Shells 1- 89



Module Orientation (Reference Concept)



Requirements and Constraints for FMA Systems Study

- Alignment Requirements
- Mass Requirement
- Thermal Requirement
- Number of modules
- Module Dimensions

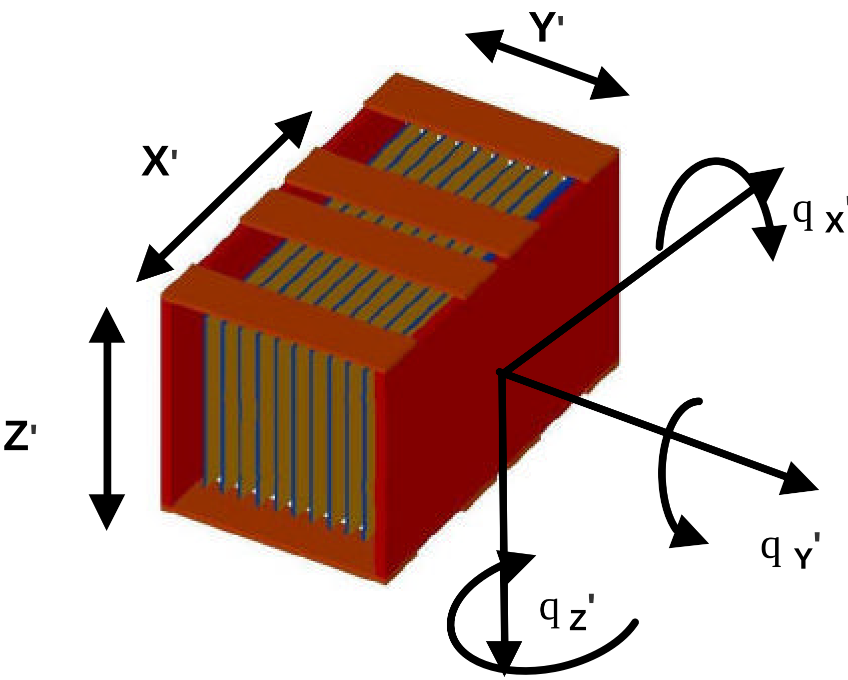
Grating Module Alignment Overview

- Individual grating modules must be aligned in a Rowland Circle geometry as shown previously
- RGS contractor will be responsible for computation of grating alignment data which will be verified by both NASA and FMA contractor
- Individual gratings within grating modules will be aligned by the RGS contractor
- Grating modules (supplied by RGS contractor) are integrated and aligned within a grating integrating structure (GIS):
  - FMA contractor responsible for this activity, supported by RGS contractor
- Method of attachment of grating modules to integrating structure is open for study
- Grating integrating Structure can be one or more monolithic structures or an integral part of the FMA. Open for Study.
- Optimal arrangement of modules is open for study.

Grating Alignment Requirements

- Each grating module must be positioned in three degrees of translation at a designated location relative to FMA coordinates
- Mechanical positional references will be provided on each grating module
- Each grating module must also be positioned in all three degrees of rotation, at designated angles relative to FMA coordinates
- An optical reference flat (which may be a grating surface) will be provided as a reference for angular alignment about the two axes nominally in the plane of the grating surfaces.
- Angular alignment about the grating normal (less critical) is done relative to mechanical references on the module
- Two sets of tolerances:
  - "Average error": Average error of grating module from required position (I.e., GIS-to-FMA tolerances in the reference concept)
  - "Differential error": Allowed error of any individual grating module with respect to the average (i.e., Module-to-module tolerances in the reference concept)

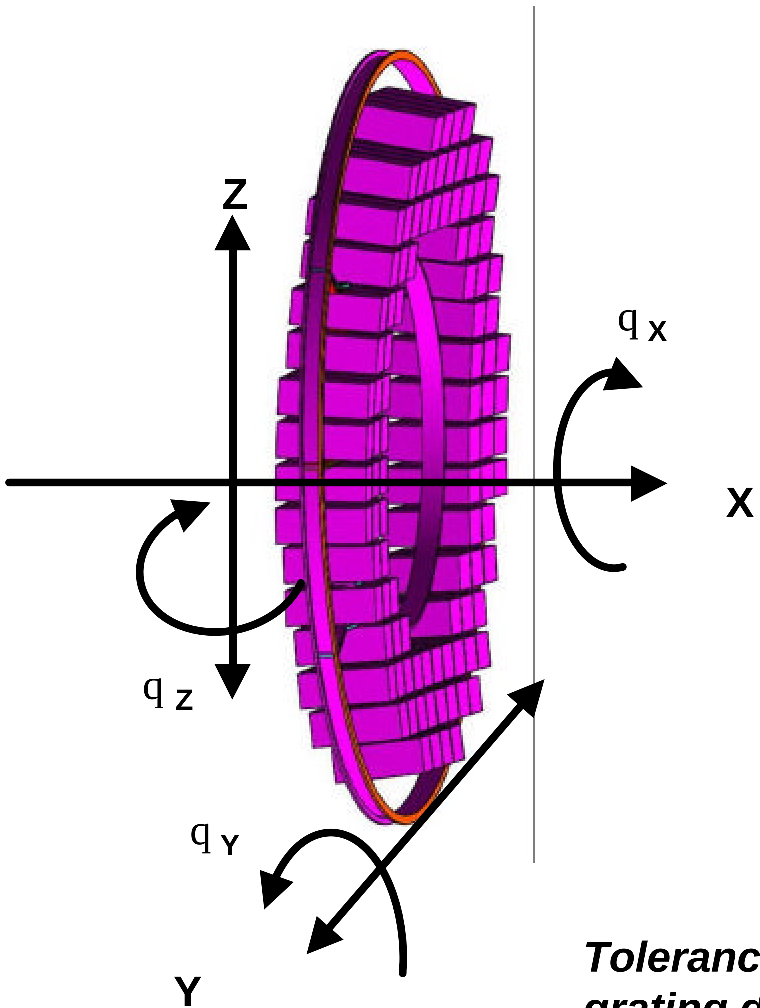
Grating Module Differential Alignment Stability Tolerances



Term (local coords)	Tolerance
X'	0.50 mm (TBR)
Y'	0.30 mm (TBR)
Z'	0.50 mm (TBR)
q_{X}'	30 arcsec (TBR)
q_{Y}'	1 arcmin (TBR)
q_{Z}'	2 arcsec (TBR)

"Prime" module (a virtual module on the optical axis) is shown. For other modules, tolerances apply to "local" X',Y',Z' coordinates, where Y' is the grating normal.

Grating Module Average Alignment Tolerances



Term	Tolerance*
X	1.0 mm
Y	1.0 mm
Z	1.0 mm (TBD)
q_X	5 arcmin (TBD)
q_Y	1 arcmin (TBD)
q_Z	15 arcsec

Tolerances are measured with respect to the focus (since grating design is based on grating-to-focus distance.)

Thermal, Mass and Mechanical RGS Requirements

Item	Requirement
Mass per grating module	0.55 kg for each grating module
Module number	100
Module size	~11 x 11 x 22 w taper
Operating Temperature Range and uniform thermal variation	20^{o} C $\pm$ 5^{o} (TBR)
Operating Temperature Gradient (along mirror axis)	Sufficient to meet alignment requirements
Operating Temperature Gradient (radial)	Sufficient to meet alignment requirements
Mechanical Stability of RGA	Sufficient to meet alignment requirements

Reference Documents

- Reference Design:
- Constellation-X Technology Readiness and Implementation Plan (TRIP) Report
- References — In-plane Gratings:
- Brinkman, et al. 1998, in "Proceedings of the First XMM Workshop: Science with XMM", ESTEC, Noordwijk, The Netherlands, ed. M. Dahlem,
- Den Herder, et al. 2001, A&A 365, L7
- http://xmm.vilspa.esa.es/external/xmm_user_support/documentation/technical/RGS/

Summary

- Tasks for FMA Contractor
- Assemble and align grating modules within a grating integrating structure (GIS)
  - Method of attachment of modules to GIS is open for study
  - GIS can be monolithic or compound
- Requirements and Constraints
  - Module dimensions are constrained
  - Modules cover outer annulus with optimal packing (~100 modules)
  - Mass limits
  - Temperature limits
  - Module-to-module alignment tolerances
  - Grating Integrating Structure-to-FMA alignment tolerances

Constellation

The Constellation X-ray Mission

Reflector Alignment and Assembly

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Optical Alignment and Thin Film Coatings
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Outline

- Points of this talk
- Introduction
- Alignment philosophy
- Metrology tools in reflector studies
- Alignment housings (OAP1 and OAP2)
- Reflector characteristics
- Alignment schemes (baseline and alternatives)
- Summary

Point of This Talk

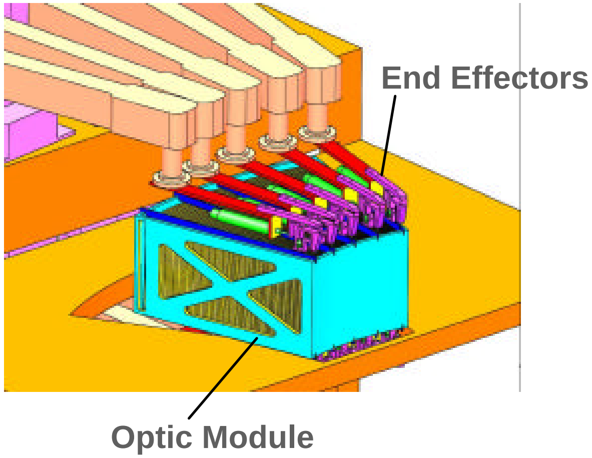
- There are no requirements included in this document
- Concepts included here are only for your information
- We will try to illustrate where some of our error budget terms come into play during alignment
- Contractor receives reflectors that, when aligned kinematically in P+S pairs, yield a 9.9 arcsec HPD image quality
  - The alignment process begins from there
  - Alignment and assembly task goes up to the module level (combined P+S units)

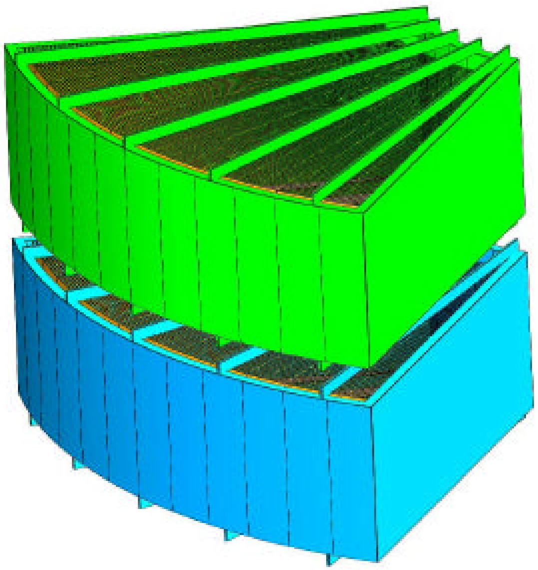
Introduction

- What is the reflector alignment and assembly task?
  - Take individual reflectors and co-align them in P+S pairs
  - Alignment can be performed on either individual reflectors or groups of reflectors, and in separate modules (P vs S) or as a whole Wolter-I unit.
  - "Perfect" P+S reflector pairs start with 9.9 arcsec HPD. The alignment and assembly process may only introduce another 5 arcsec HPD to the image
- Alignment concept chosen is dependent on what kind of metrology and housings will be used during alignment and assembly

  or…

- The metrology used during alignment and assembly will depend on the alignment concept





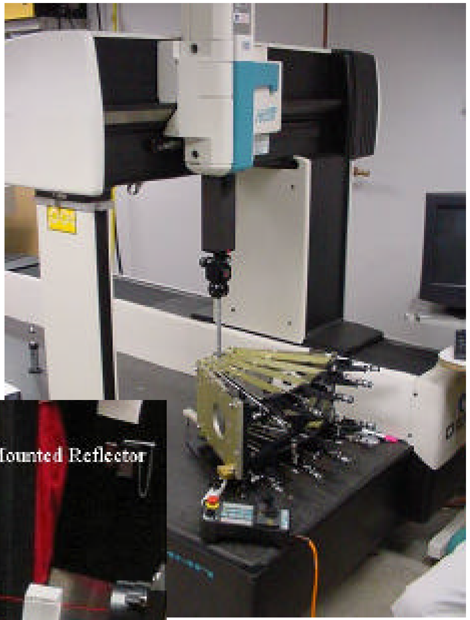
Alignment Philosophy for FMA Reference Concept

- Each reflector is highly over-constrained
  - Kinematic mounting for each segment may not be possible
  - Alignment must correct cone angle and average radius errors resulting from reflector fabrication
- Reflector alignment must correct reflector focus and properly position the image, without introducing more than ~ 6 arcsec HPD distortion and alignment error.
  - Alignment process must correct for average cone angle, radius of curvature, radial position, and segment tilt and twist to achieve required performance.
  - Average cone angle - Must be corrected with high fidelity. Determines the axial position of best focus (sensitivity ~ 1.25 mm/arcsec for shell 1, ~ 6.6 mm/arcsec for shell 230).
  - Radius of curvature (average radius error) - Focus is moderately dependent (~ 0.8mm/25um for P, shell 230, and ~ 2.5mm/25um for S, shell 230, and proportional to graze angle). HPD is weakly dependent upon average radius error
  - Segment tilt or twist - Rotation of the reflector around a tangential or radial axis . Produces aberrations strongly impacting HPD (~ 1 arcsec/um)
  - Radial position – Produces aberrations impacting HPD
  - Circularity – Limited ability to correct due to limited sampling by CDA. Circularity errors are budgeted and included in the 9.9 arcsec reflector HPD and therefore need not be corrected via alignment. However, alignment correction of low-order circularity may prove advantageous.
- Non-rigid body (i.e., bending) alignments – average radius, cone angle, and circularity – introduce axial and azimuthal figure error. Need to minimize figure errors introduced during alignment process.
  - May be necessary to trade/balance errors corrected with those introduced

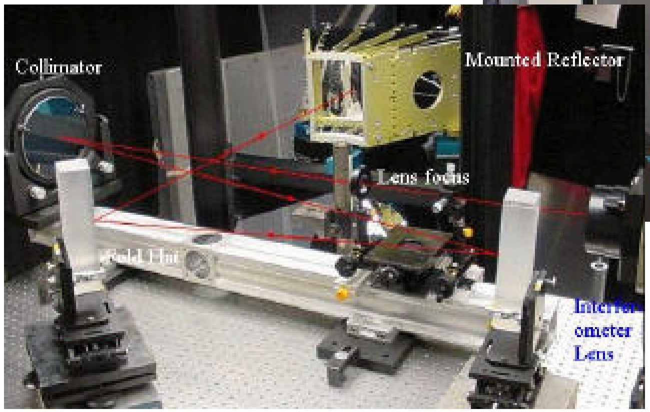
Metrology Tools Used in Reflector Studies

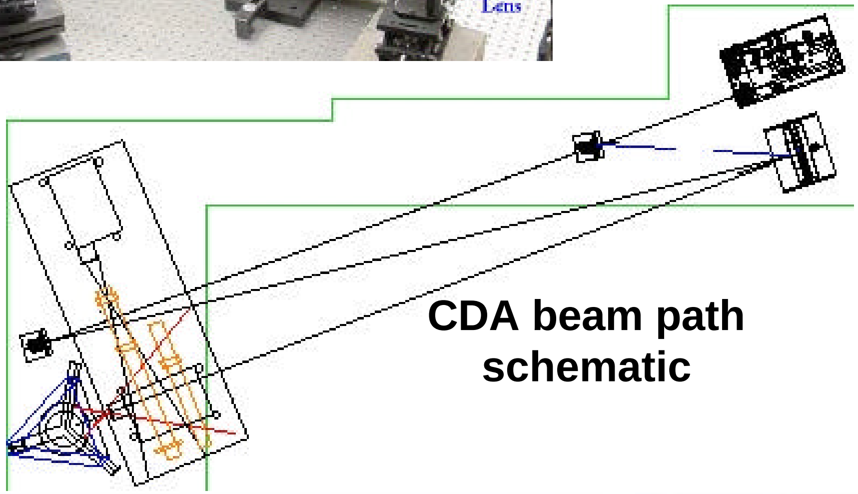
- Coordinate Measuring Machine (CMM)
  - ~2 micron position accuracy
  - Used to locate the front surface of each reflector to the designed radial position at multiple top and bottom points
- *In-situ* axial interferometry
  - Measures axial figure of individual axial strips
  - Late breaking measurements indicate that stitching images from small CGHs may provide global 3-D mapping of reflector surface
- Centroid Detector Assembly (CDA)
  - Used to measure to the focus position of each reflector at a number of points along azimuth
  - Can access all reflectors in a module
- Combine image location data (CDA) with image blur data (interferometer) to predict HPD of reflector or P+S pair

CMM



Interferometer

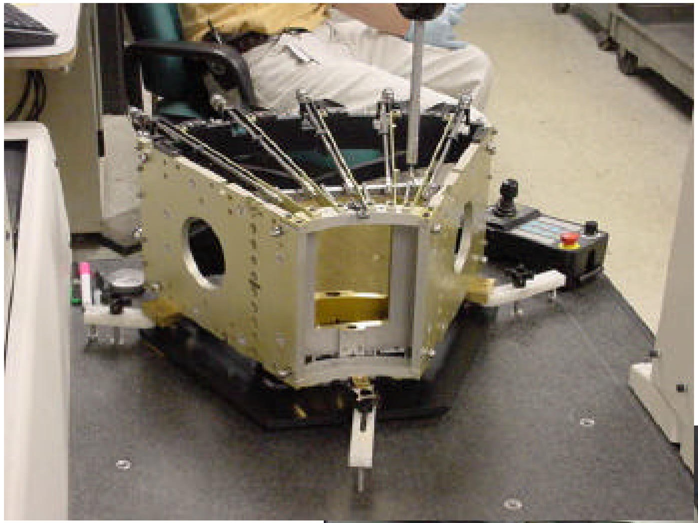




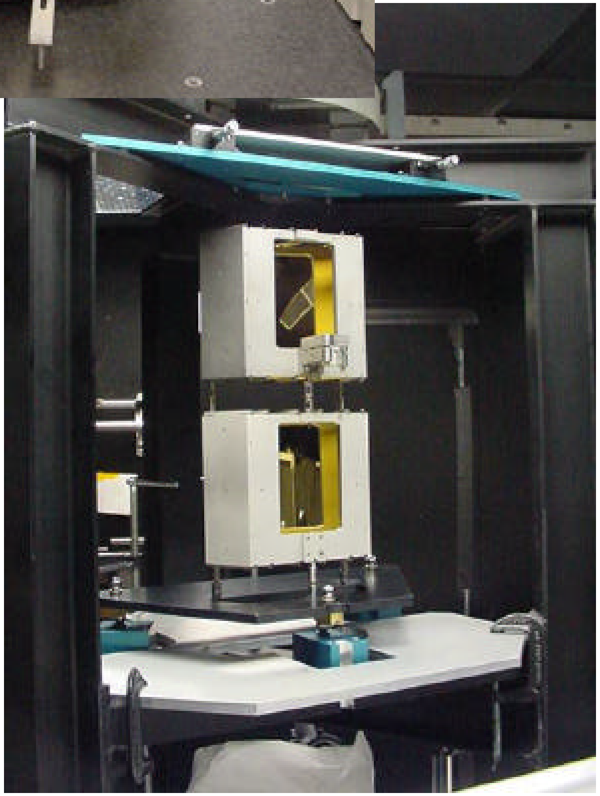
CDA beam path schematic

Alignment Housings

- Work up until now has concentrated on individual thin glass reflector behavior under the constraints of the Optical Alignment Pathfinder (OAP1 and OAP2) systems
- OAP1 designed to hold a reflector and adjust it at multiple points along the top and bottom of the reflector
- OAP2 designed to provide a low stress housing that can hold a reflector bonded in place. It can be used in vertical or horizontal orientation without imparting significant deformation on the reflector
- Each allow the use of CDA and front surface axial interferometry
- Future generation housings will incorporate characteristics that allow for mass alignment



OAP1

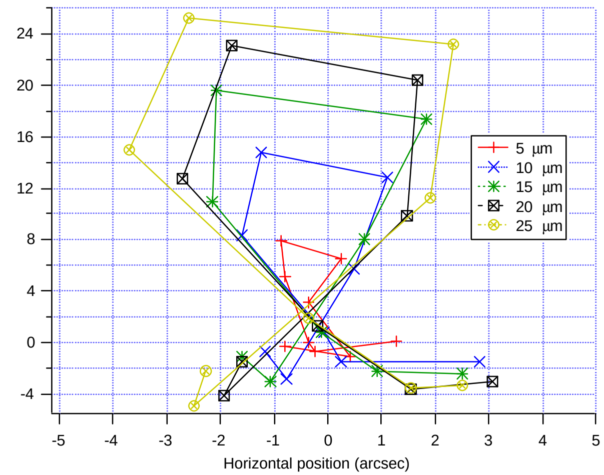


OAP2

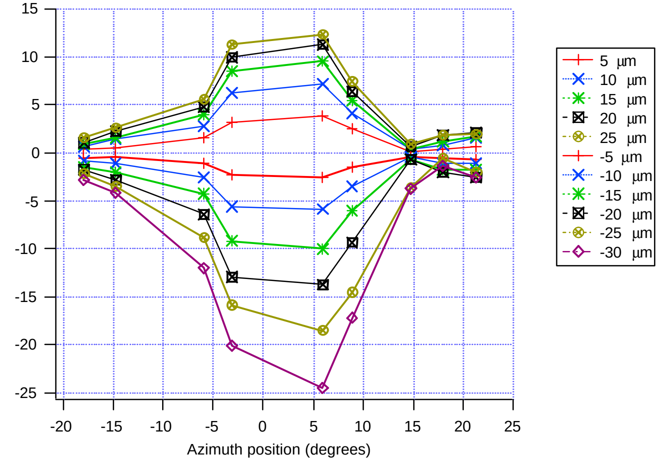
Reflector Characteristics – Cone Angle Deformations

- Reflectors are highly flexible and globally susceptible to twists
- Cone angle changes propagate from actuated position through to neighboring fixed position
- Curvature due to a deliberate deformation is smooth and well understood

Focal plane spot deviation vs single actuator movement
HS-3 (bottom center H actuator, increasing radius)

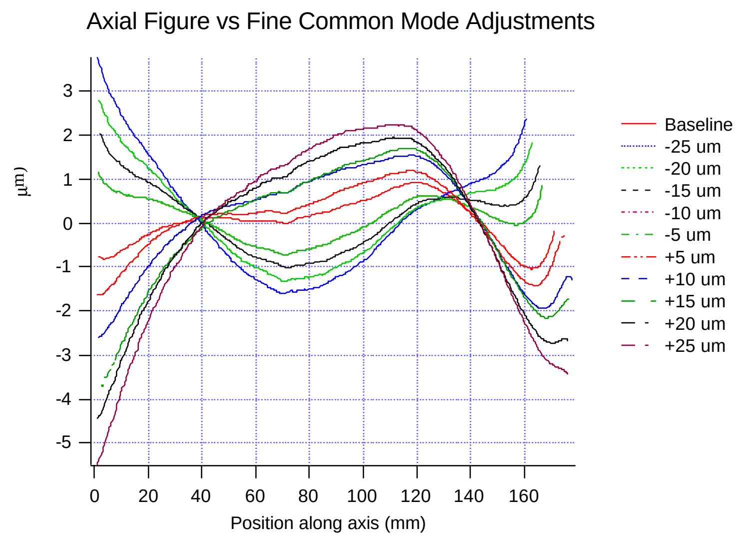


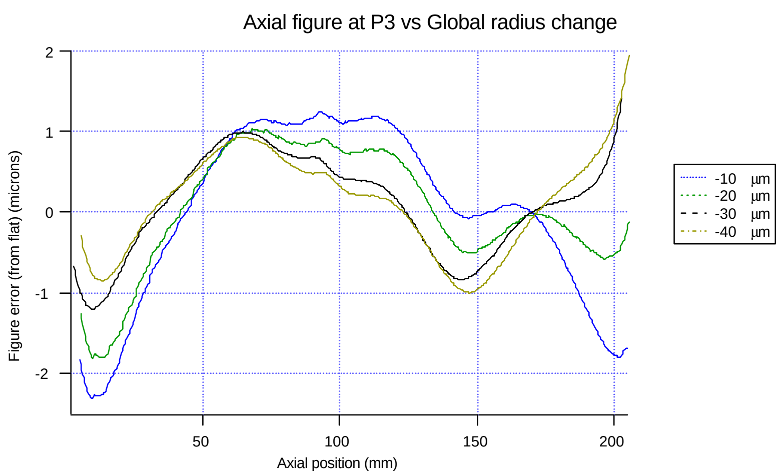
Radial displacement vs azimuth position
moving HS-3 actuator



Reflector Characteristics – Axial Sag Sensitivity

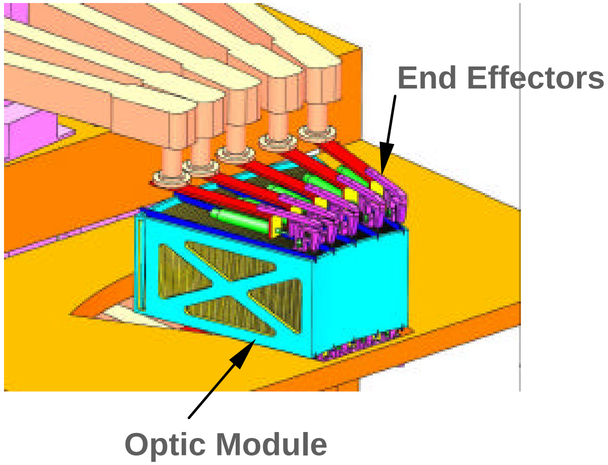
- Axial sag is very sensitive to common mode adjustment
  - Common mode adjustment = increasing or decreasing radius at top and bottom together
  - Cone angle changes should be made in differential mode
- Even small changes in global radius of curvature yield significant changes in axial figure, in this mounting scheme.
  - Axial "sag" changes by 0.05 microns per micron of radius of curvature change.
  - 10 micron change in r.o.c. -> 0.5 micron change in "sag"
- For this study we assume that the axial sag of reflectors is good while free-standing. During alignment we need to make sure axial sag is not degraded

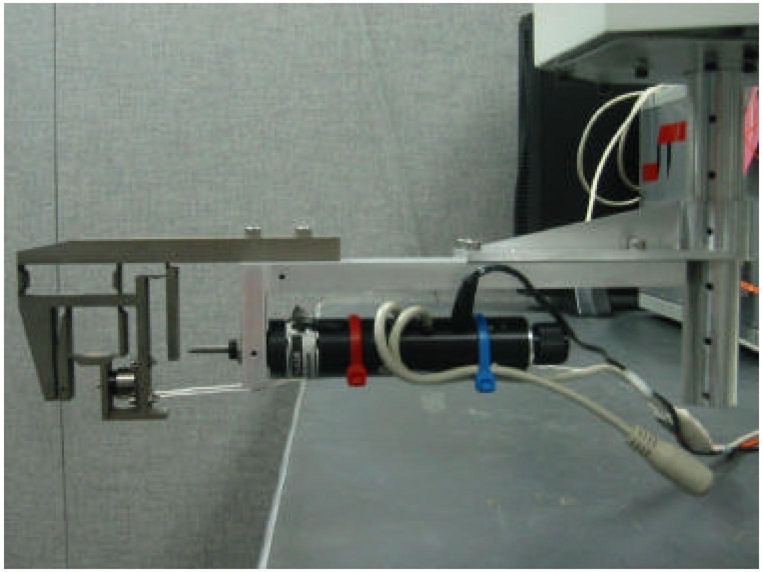




Alignment Schemes – Baseline

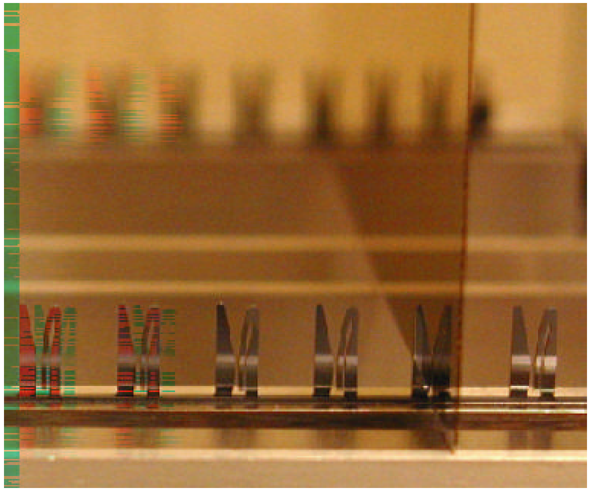
- Large number of reflectors per FMA means that alignment of each reflector must be rapid, or multiple reflectors must be aligned together
- PARAT - Precision Alignment and Robotic Assembly Tool
  - Closed loop, automated system that aligns each reflector individually, and bonds the reflectors into a stiff, modular housing.
  - Uses CDA and in-situ axial interferometry to gauge figure and cone angle
  - Robotic arm can cover the entire range of a sinlge module
  - Can such an arm reach between the P and S housings?
  - Either need to insert each reflector individually (in order to use interferometry to get axial figure) or assume that the axial figure is maintained, or use some other method to gauge axial figure.





Alignment Schemes — Alternatives

- Silicon Alignment Combs
  - Uses a precision inner reference cylinder and reference surfaces to place top and bottom of each reflector at designed radial position
  - Analysis has shown that stack up errors make this a very difficult method. Also has no provision to monitor axial figure errors
- Use silicon combs to align multiple reflectors as once in baseline-style concept
  - Assumes any axial figure changes occur uniformly through all reflectors being aligned
- "HEFT" build-up concept
  - Built up from inside out
  - Place ribs on back of previous reflector
  - Machine ribs to required axial figure (verify with precision CMM or other tool)
  - Attach next reflector to machined ribs



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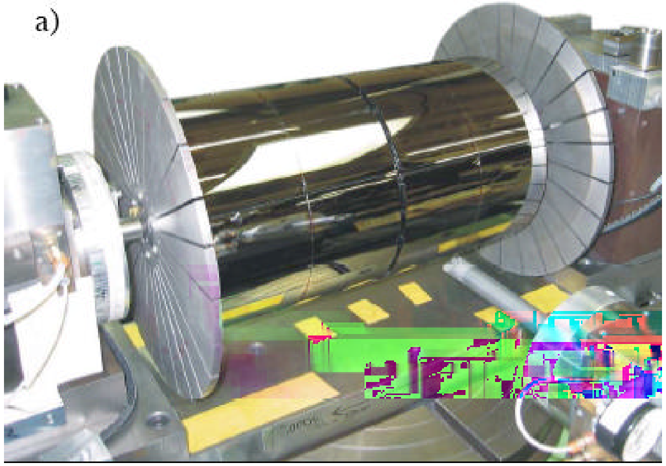

Summary

- Start with reflector pairs that have 9.9 arcsec HPD image quality
- Take these reflectors and put them in modular housings without imparting any more than another 5 arcsec HPD error
- Monitor axial figure during alignment to keep from increasing beyond the original 9.9 arcsec value
  - Axial figure is extremely sensitive to positioning deformations
- A variety of alignment schemes can be considered, using different metrology tools
  - None of them, as of yet, have been shown to solve all of our problems

Constellation X

The Constellation X-ray Mission

Reflector Metrology for the Constellation-X Soft X-ray Telescope

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Outline

- Introduction — Why Is This Hard? Why Is It Different?
- Low Order Metrology — Dimensions, Shape
- Circularity
- Axial Figure Metrology — Comparison of Methods, Noise
- Midfrequency and Microroughness
- Summary

Note on Optical Metrology Requirements

- **All requirements to be shown here are derived from the overall optical imaging error budget;**
  - Ref: Presentations by W. Podgorski (Error Budget & Systems Analysis) and T. Saha (Optical Design)
- **As such, these are DERIVED requirements intended to ensure that the image error contributions from metrology are small (typically ^{3}10% in an rss sense) as compared to the requirements on substrates, replicated reflectors, mandrels, and optical assemblies.**
  - We also are responsible for testing formed substrates as feedback to the fabrication process

Mirror Comparison Table – Aspect Ratio

	Units	AstroE2	Chandra	XMM	C-X SXT reflectors		
					OAP	Prototype	Flight (20cm)
Largest mirror radius	mm	106	600	350	247.5	800	800
angular width	degree	90	360	360	56	30	30
arc length	mm	167	n/a	n/a	241.9	418.9	418.9
axial length, per reflection	mm	100	840	300	200	200	200
part diagonal	mm	194	n/a	n/a	314	464	464
substrate thickness	mm	0.155	20	0.85	0.4	0.4	0.4

Stiffness scales as thickness^3, so the SXT reflectors are much less stiff than all previous missions except AstroE2

HPD ^{x}Areal Density – Mirror Difficulty Metric?

Table 2: HPD, Areal density, and product comparison among missions

Mission	Mirror Material	Density	Thickness	Areal Density	Required HPD	Product HPD ^{x}Areal Density
Units		kg/m^2	mm	kg/m^2	arcsec	arcsec^{x} kg/ m^2
Asto E2	A1	2700	0.2	0.4	90	38
Chandra	Zerodur	2530	20	50.6	0.5	25
C-X SXT	Desag 263	2510	0.4	1.0	12	12
ROSAT	Zerodur	2530	20	50.6	3	152
XMM	Ni	8908	0.9	7.6	15	114

Metrology Requirements and Performance Table

Requirements come from error budget – inputs from W. Podgorski (error budget[1])

Metrology requirement is allocated 10% of reflector derived requirements; in an root-sum-sqared budget, the metrology requirement is then 1/v10 of the reflector requirement for each error term

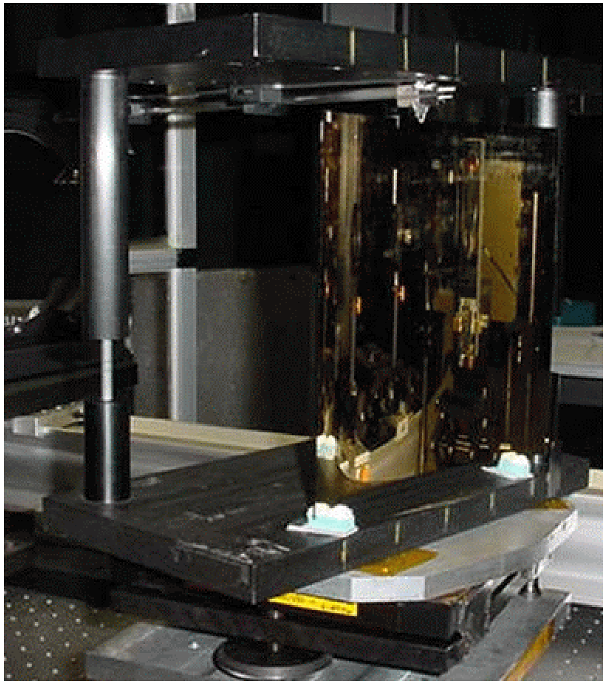
Error term	units	Reflector derived require-ment	Metrology Require-ment	Mandrel metrology: perfor-mance	Mandrel metrology: method	Substrate/Reflec-tor metrology: perfor-mance	Substrate/Reflec-tor metrology: method	note
Average radius error	um	±33	10	±2	CMM	tbd	nC CMM	3
Cone angle deviation	arcsec	±10	3.2	±5		3.2		
Delta-delta-r error, rms	arcsec	0.71	0.2	0.6		0.1	CDA	1
Roundness (in phase) or azimuthal figure, rms	um	5	1.6	0.3		(1)	nC CMM	
Axial sag error (P/V)	um	0.07	0.02	±0.01	Wyko400/ 8BX	(±0.01)	Wyko400/ 8BX	2, 4
Axial slope irregularity, rms	arcsec	2.36	0.75	0.35		0.5		
Midfrequency error, rms	nm	8	2.53	0.1	Bauer200	(0.1)	Bauer200/ Wyko400	2
Microrough-ness, rms	nm	0.4	0.13	0.09	Micro-XAM	(0.1)	Micro-XAM	

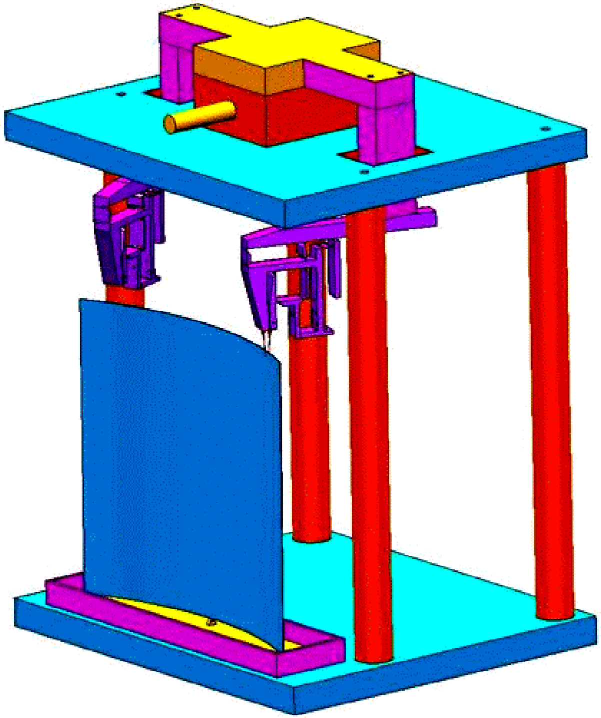
notes
1. CDA applicable to P or S substrate or replica in a housing or assembly
2. Parentheses indicate the expected value, but confirmation is incomplete on this type of part
3. nC == either non-contact or <=15mg contact force probe
4. 8BX == 8" (20cm) beam expander (built in house for 20cm axial metrology)

1)W. Podgorski et al., SPIE 4168-35 (2003)

Fixturing Issue for Substrate/Replica Metrology

- Requirements for fixturing these parts for metrology are very difficult
  - Distortion must be minimized
  - Any distortions must be highly repeatable and correlated with FEM
  - Consensus is a near-kinematic mount, correlated w/ models & cross-checked
  - We are still working on this
  - Examples of mounts we are testing shown





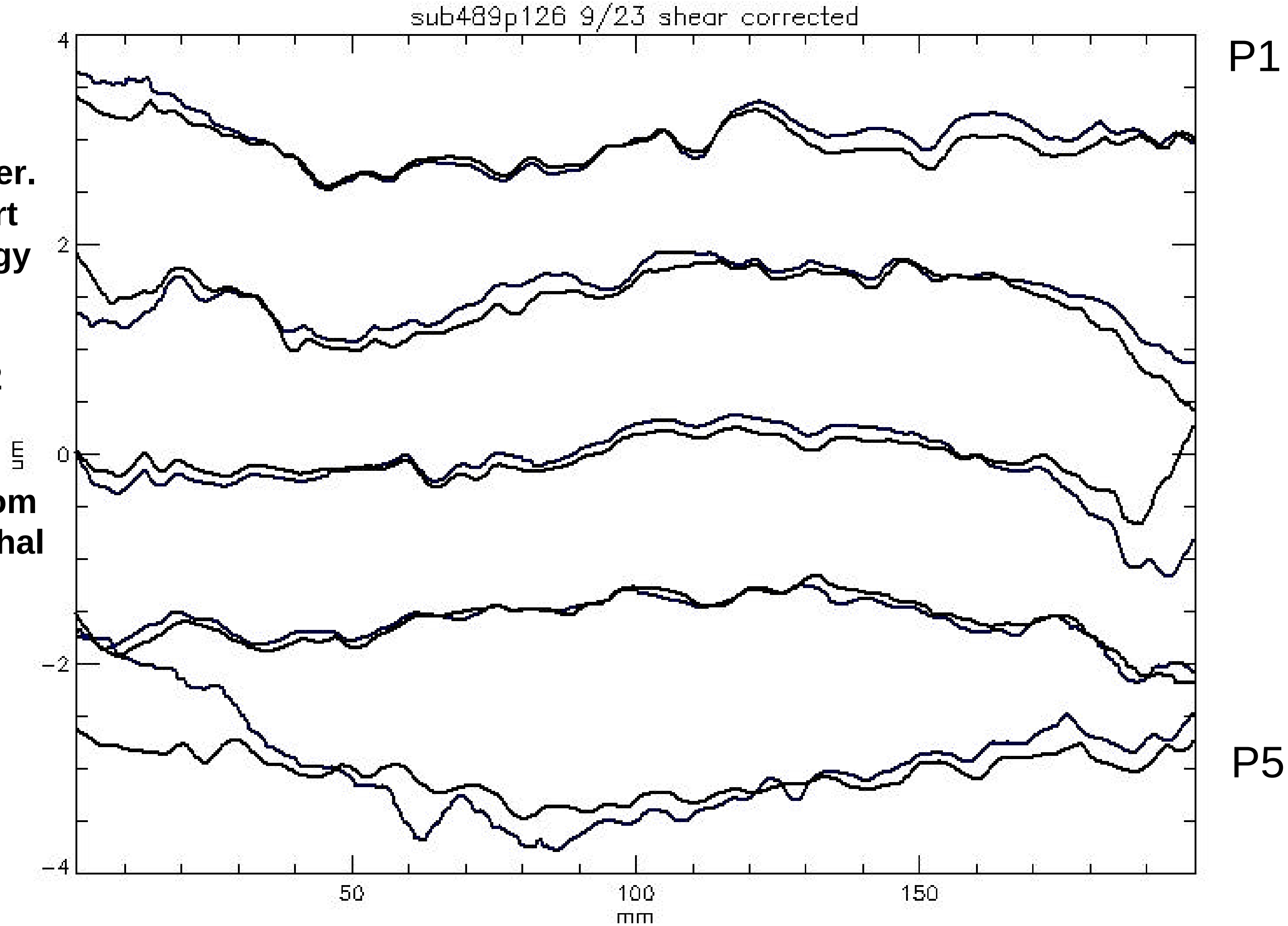
Example – Axial Data Repeatability After Removal & Reinsertion Into a Test Fixture

Part is a primary substrate, 20cm axial length, ~50cm diameter. We have used this part for extensive metrology checks

Curves are offset by 2 µm for clarity

P1/P5 are ~1/2 way from center to each azimuthal edge

9/22 & 9/23 data with shear corrected (no polynomial removal)



Summary

- The SXT reflectors have tight requirements relative to their stiffness; this places extra constraints on the metrology
- Mandrel metrology is well in hand
- Axial metrology on substrates & replicas is also in good shape
  - We are still working on the best fixturing method for substrates and replicas
- Midfrequency and microroughness correlate with the axial data
- Microroughness has been confirmed by x-ray scattering
- The metrology to map radial errors across the full aperture of substrates and replicas is not yet meeting requirements
- The remaining charts show examples of metrology setups and example data

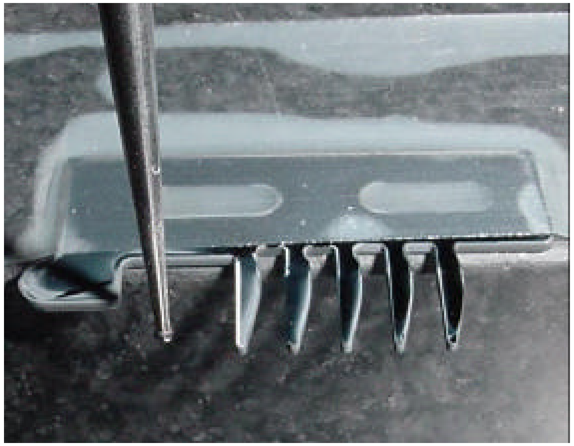
Reference: D. A. Content, D. Colella, C. Fleetwood, T. Hadjimichael, T. Saha, G. Wright, W. Zhang, "Optical metrology for the segmented optics on the Constellation-X soft x-ray telescope," Proc. SPIE [5168-23] (2003).

Backup Slides

Moore#3 CMM

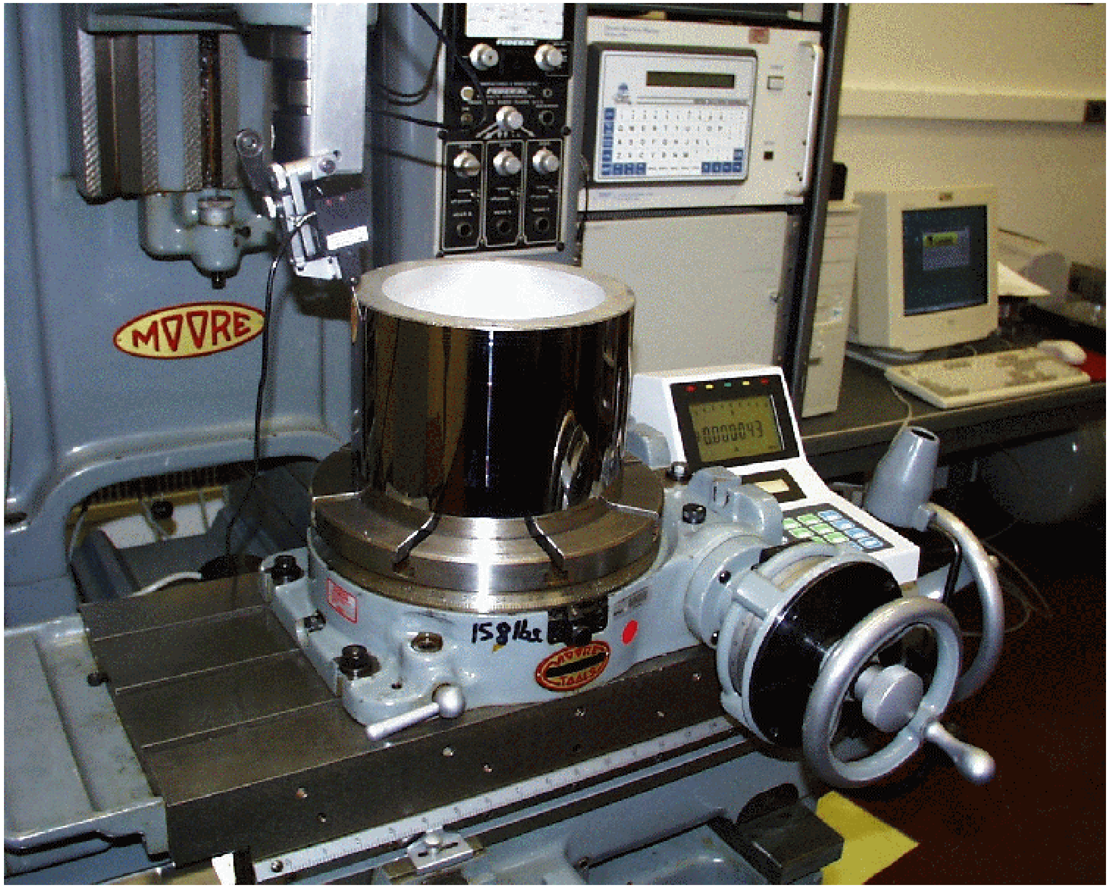
- Mechanical table with 3 axis interferometric position sensing
- Contact and non-contact probes
  - Currently using low force probe for substrates and replicated reflectors
- ~225 mm longest axis of linear travel
- Rotation stages allow measurement of circularity using a fixed probe

Moore Probe
(testing MIT alignment micro-comb)



Moore#3 Circularity

- Requirement – 2.4 microns
  - Contact or non-contact stage should be <= 0.3 microns performance
- Tooling required
  - Heavy-duty rotation stage
    - Either ~um level runout or excellent calibration & repeatability of axial runout
- Our setup is fairly slow, ~1-2 measurements /day



Example CMM Contact Measurement Result on an OAP (~50 Cm Diameter) Forming Mandrel

Measured parameter	Midpoint Diameter		Cone Angle	
F494S	**value**	**units**	**value**	**units**
nominal value	490.87	mm	1.2554	degree
tolerance	0.20	mm	30	arcsec
error from specification	0.16	mm	3.9	arcsec
metrology uncertainty requirement	0.070	mm	10	arcsec
metrology uncertainty	0.002	mm	9.2	arcsec

Uncertainty determined by 1-sigma statistic on repeat measurements

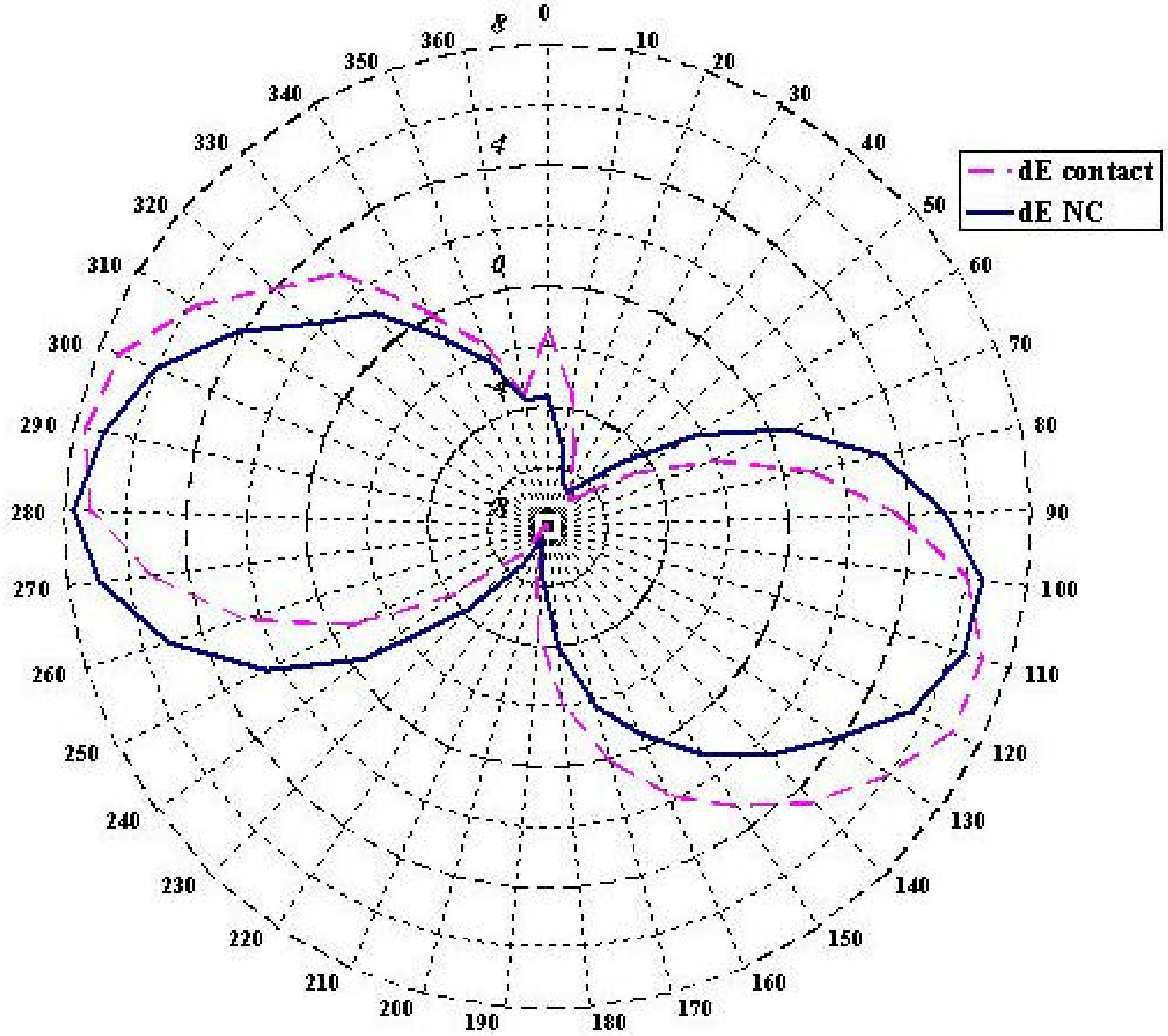
Comparison of Azimuthal Figure Error as Measured by Contact and Non-contact Probes

RMS out of roundness ~ 5 um with either method

Repeatability of either method is < 0.2 um rms

The two measurements agree to < 2 um rms

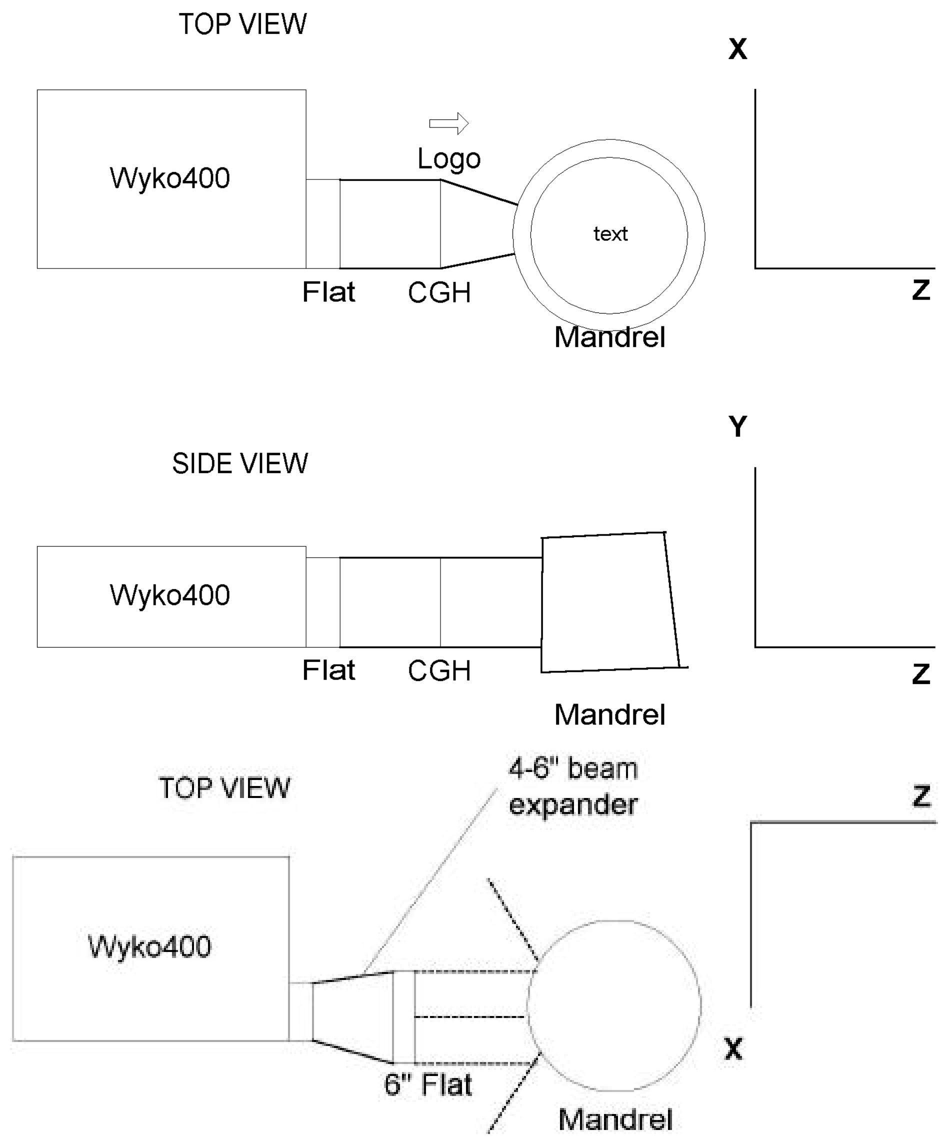
Apparent 10 degree shift is <u>not</u> a result of misalignment



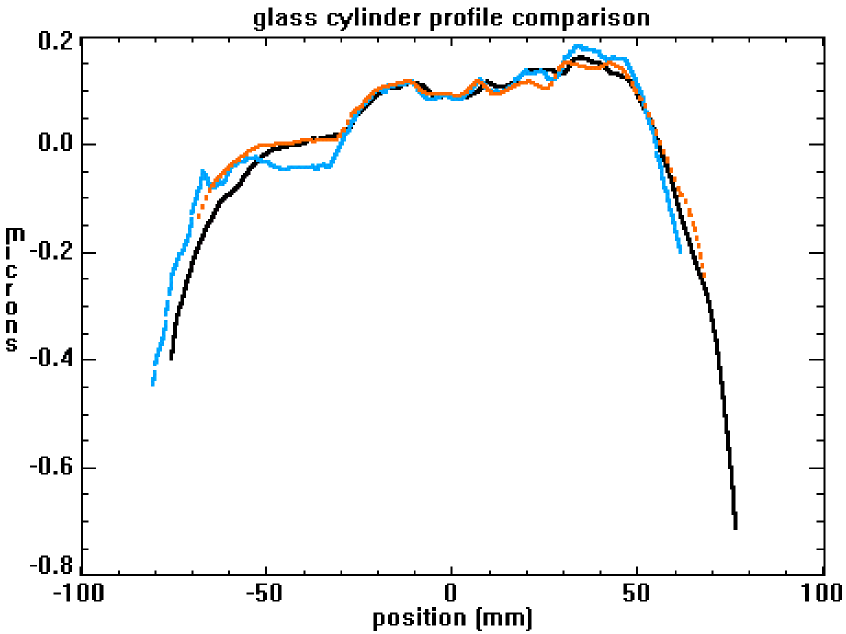
Different Layouts for Axial Profiling of Mandrels and Replicas

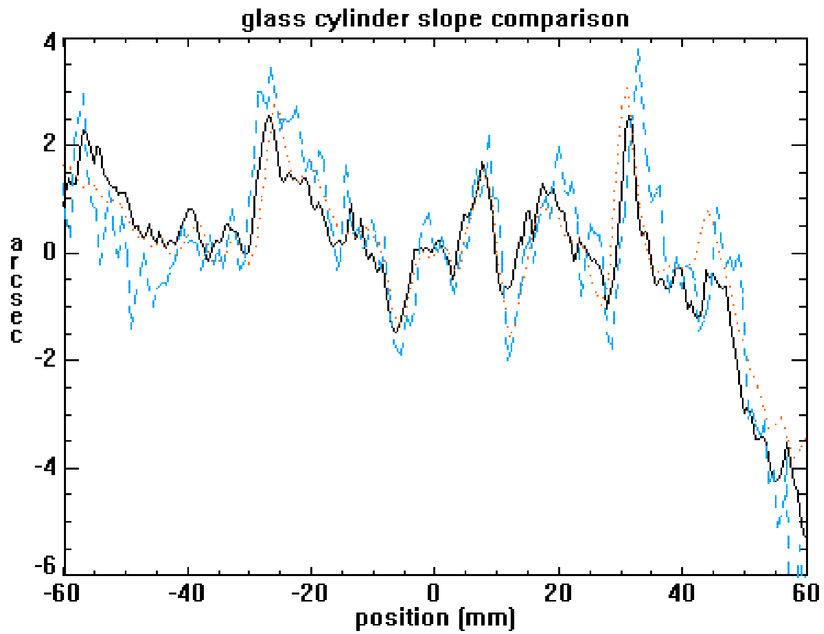
Top:
CGH Cylinder/cone Wave Layout

Bottom:
Plane Wave Interferometer Layout



CGH, LTP, and Collimated Beam Profiling Comparison

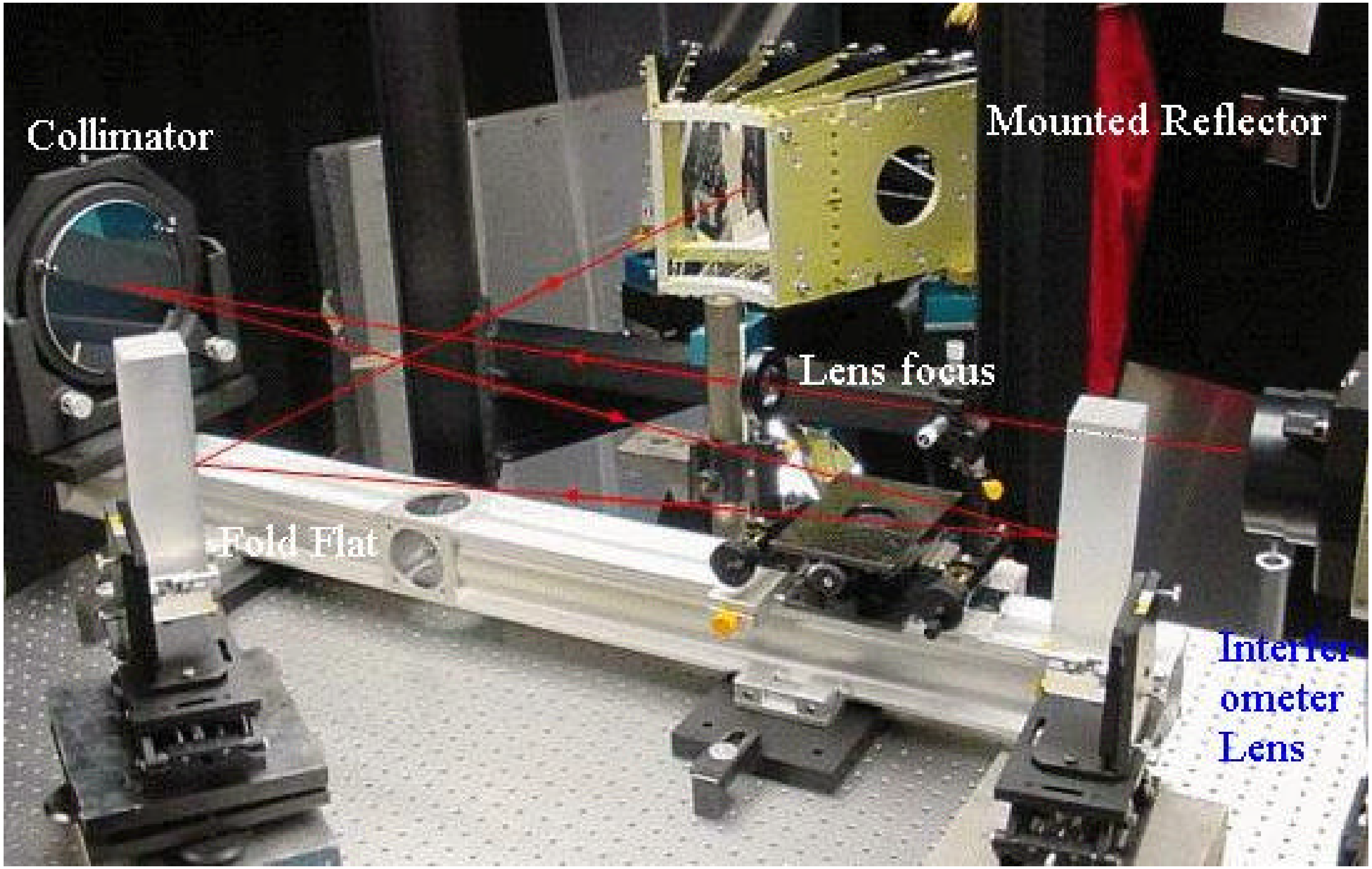




Black: CGH interferometry; blue dashed: collimated beam interferometry; red dotted: LTP

Agreement is <=50 nm in profile and < 1 arsec in slope

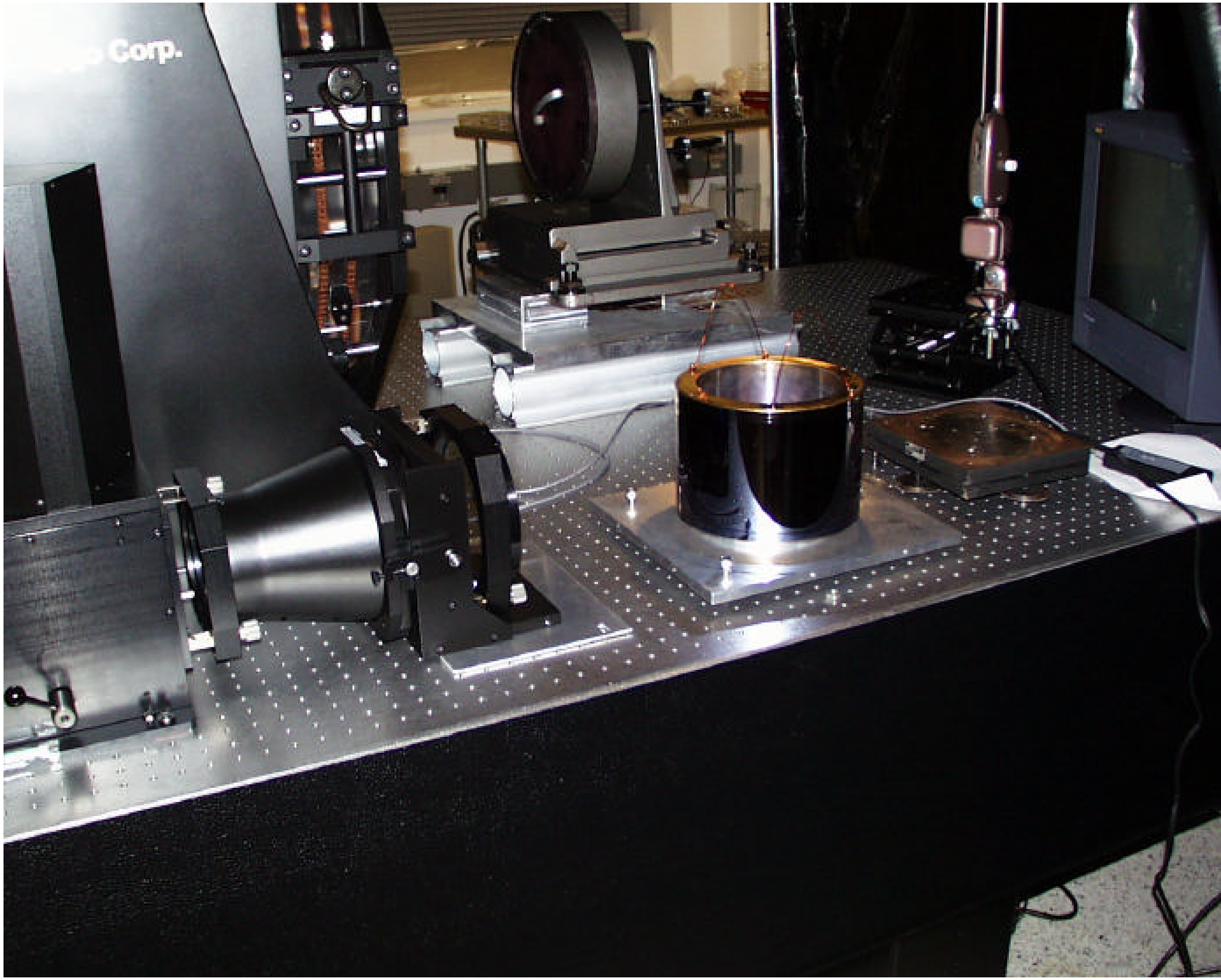
In-situ Axial Figure Station



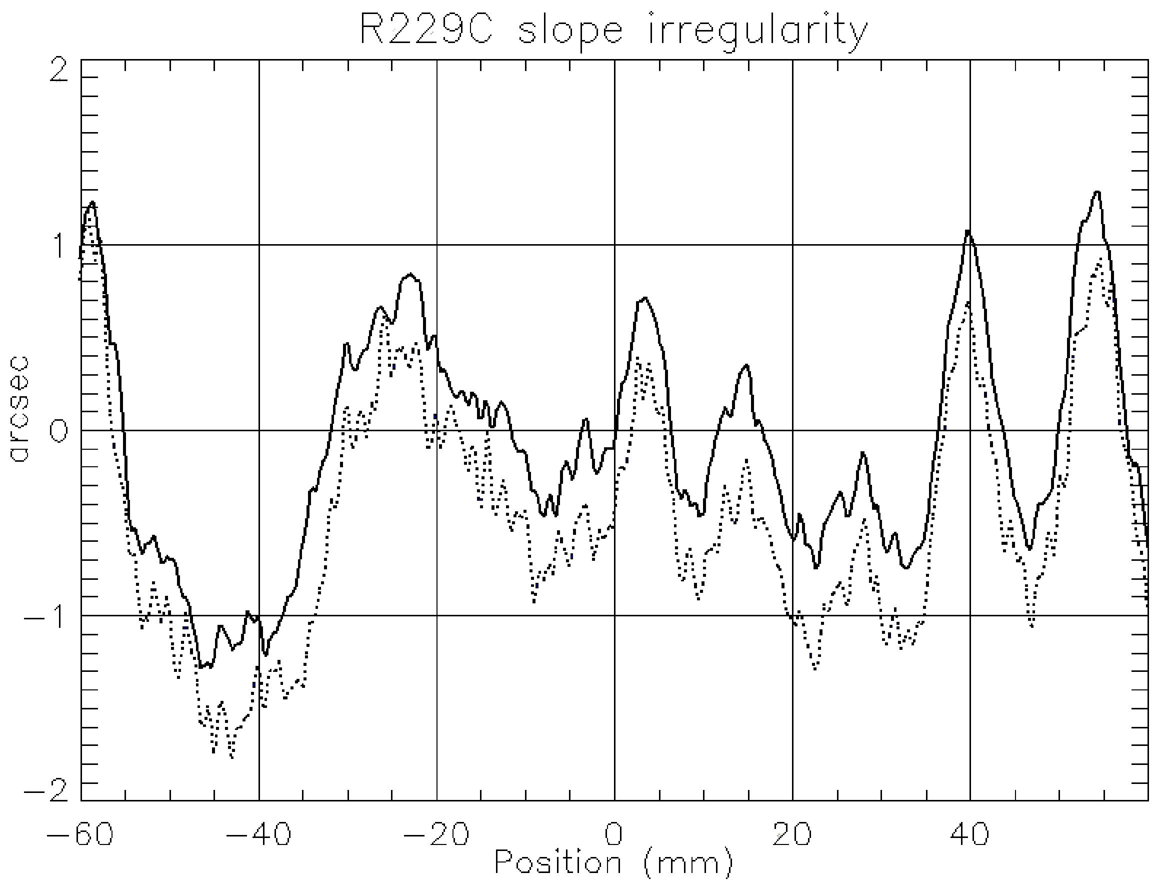
60 cm Aperture Zygo Interferometer

This will be used to measured the OAP forming mandrel figure and other large (OAP, Pathfinder, etc) mandrel figure measurements as required.

We also plan to use it for the stand-alone substrate and reflector axial figure measurements



Axial Metrology



Repeatability of the axial slope irregularity (derivative of profile); as measured on a replication mandrel figured in-house at GSFC. Curves are offset by 0.5 arcsec for clarity

Midfrequency Metrology (~40 to ~0.5 mm Period Errors)

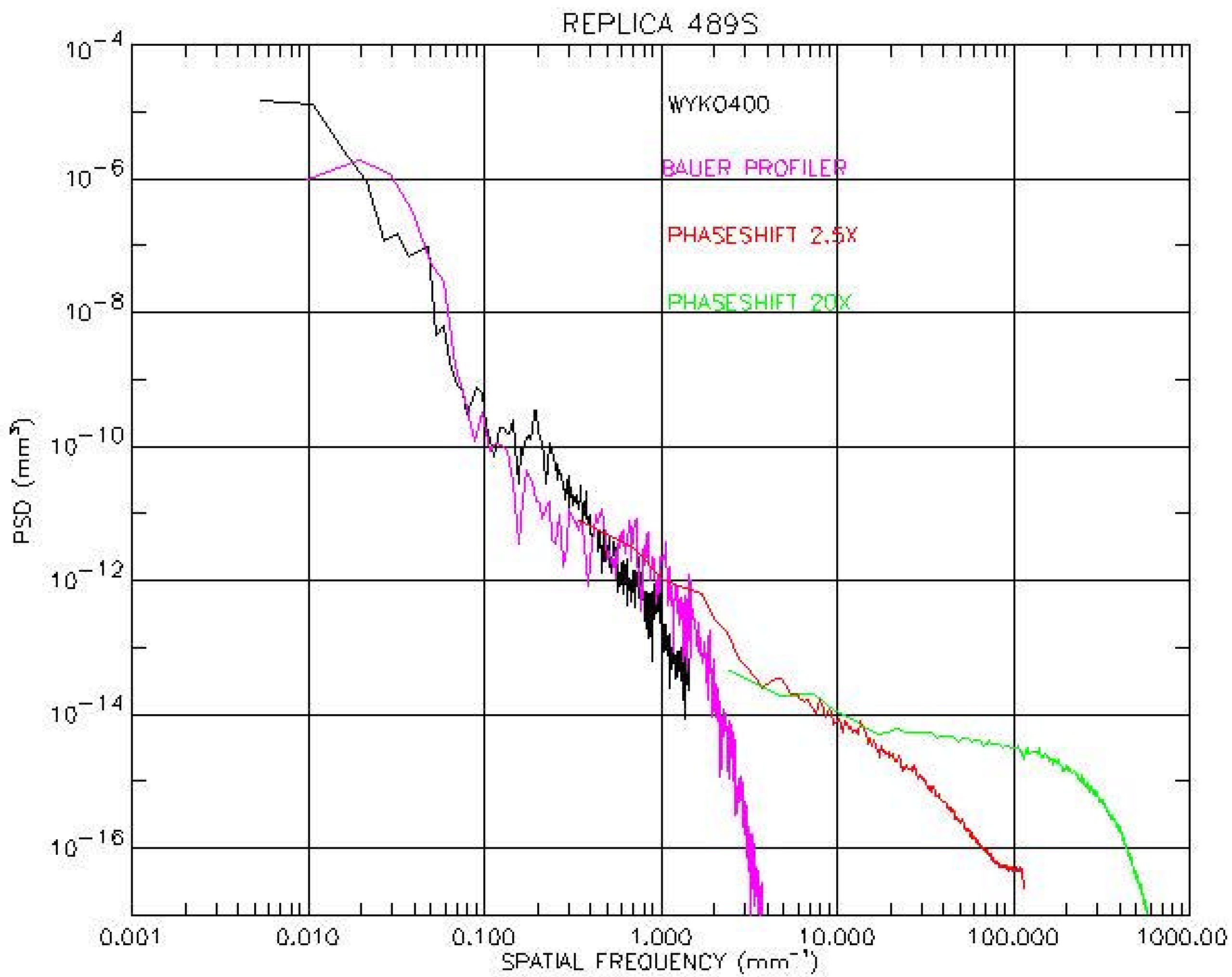
- Midfrequency — Bauer200
- Current Bauer200 configuration – suitable for parts =20cm axial length

Power Spectral Density Comparison on a Reflector Among Axial Interferometry, Midfrequency Profiling, and Microroughness

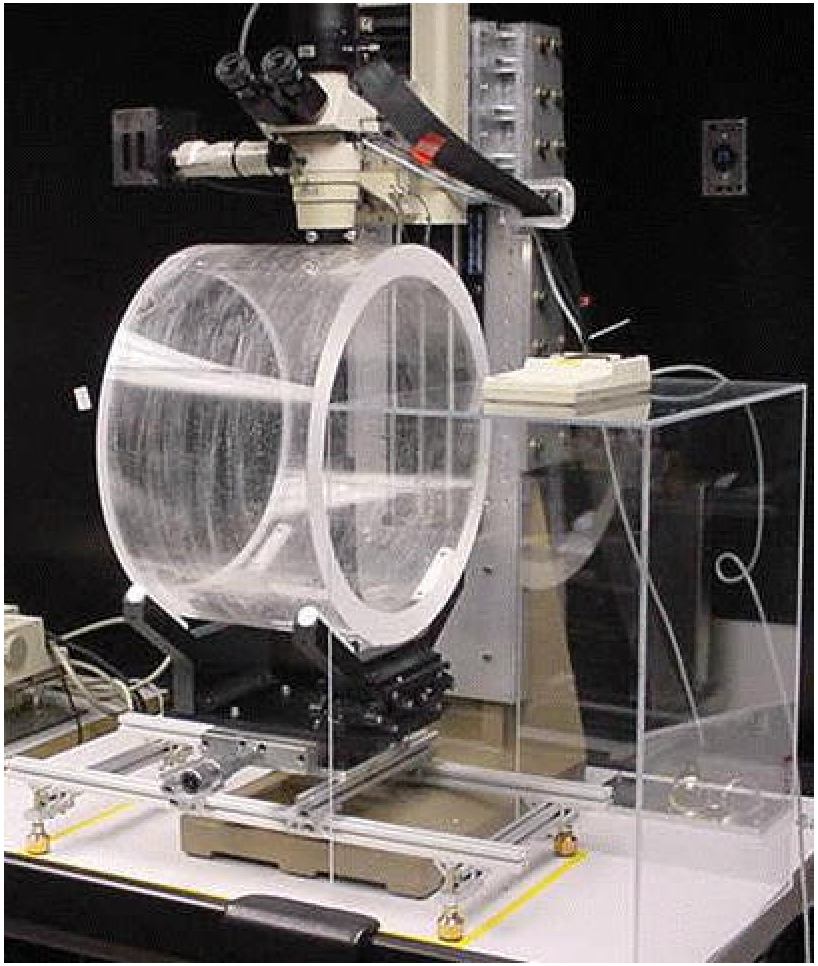
Part is a primary reflector, 20cm axial length by ~50cm diameter, from mid 2003

Each PSD has a noise-limited 'tail' which should be ignored.

We plan to measure the noise-equivalent PSD for each metrology station and then only use the portion w/ PSD signal-to-noise ratio >1



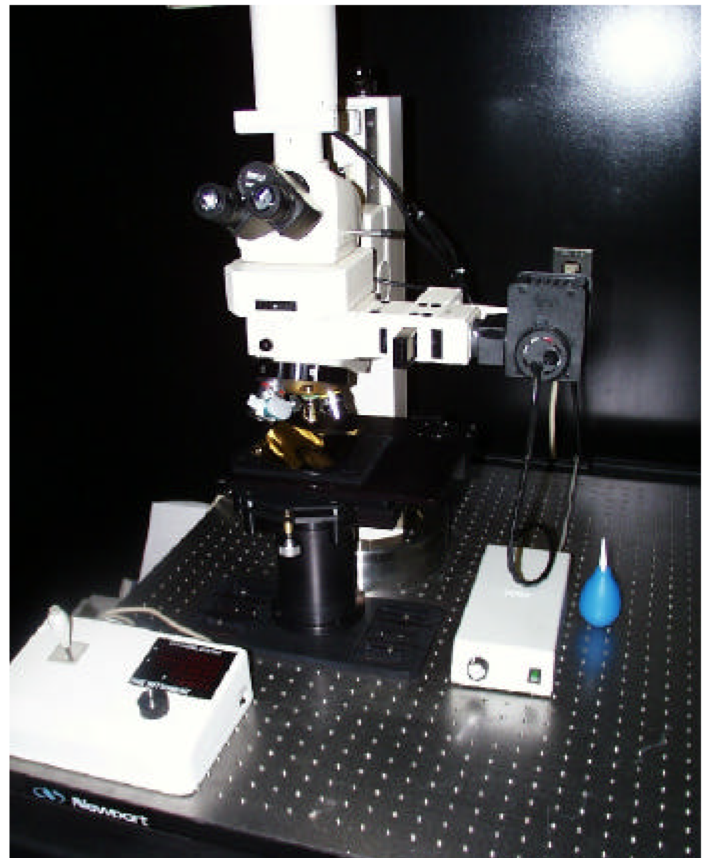
Microroughness



TOPO-3D microinterferometer, modified to measure 50cm diameter mandrels

Table 5: Roughness results on test coupon	Roughness, nm rms	
Type of test	average	std. devn.
F. Christensen/DSRI X-ray scatter	0.45	0.02
S. Owens, GSFC X-ray scatter	0.48	0.04
GSFC optical microinterferometry	0.40	0.08

Comparison of scatter on a coupon mirror polished in-house shows good agreement with roughness results from x-ray scattering measurements done at GSFC and at DSRI



ADE PhaseShift "MicroXAM" micro-interferometer, usable for substrates, replicas, and small (AstroE scale) mandrels

Constellation

The Constellation X-ray Mission

Thermal Control

Mark Freeman/SAO
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Outine of FMA Thermal Requirements Presentation

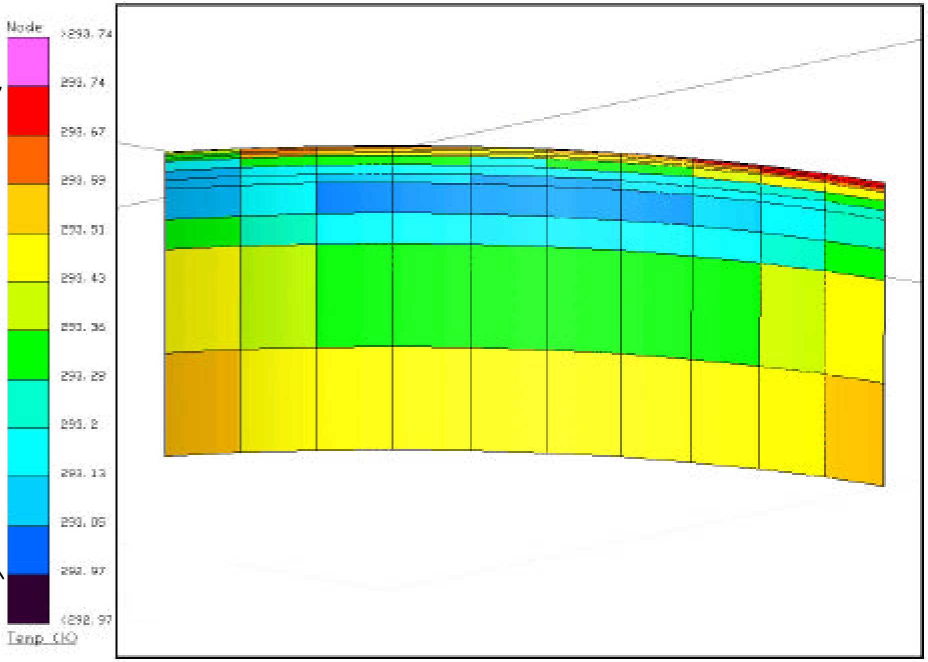
- Basic Thermal Requirements
  - Temperature Requirements Flowdown
  - Power Requirements Flowdown
- Thermal Design Issues for closely-packed Wolter-I Optics
- Pre-collimator Design for the Reference Concept
- Pre-collimator Modeling Demonstrates Feasibility
- Considerations for Contractor Design Work

FMA Thermal Requirements

FMA Thermal Requirements		Source
FMA Power Requirement	< 400W	FMA Requirements Document
FMA Temperature Requirement	Consistent with FMA Angular Resolution Req't of 12.5 arcsec	FMA Requirements Document
Interface Environments for Power Estimate	0C for Optical Bench	FMA Requirements Document
	5C for Spacecraft	
Derived Temperature Requirements for Reference Concept		
Mirror Radial Gradient	< 0.1 C per Module	Derived from contribution of thermal error to FMA Angular Resolution Error Budget (<2.2 arcsec for Reference Error budget)
Mirror Axial Gradient	<1.0C	
Mirror Diametrical Gradient	< 1.0C	
Maximum Reflector Gradient	<0.5C	
Operating Temperature	20C +/- 1C	Fabrication and Assembly Req't.
RGA Axial Gradient	TBD	To meet grating module alignment requirements
RGA Radial Gradient	TBD	
Vignetting from Pre-/Post-Collimator	Minimize	FMA Effective Area Requirement

FMA Thermal Requirements Flowdown to Reference Concept

- FMA Temperature Uniformity
  - Derived Requirement: Angular Resolution Error Budget limits the thermal contribution to ~2 arcsec
  - Derived requirement for strain-free assembly is 20C normal operating temp.
  - Flowdown requirements and issues from the Reference Concept:
    - Sensitivity to bulk temperature changes favors CTE match between glass and housing
    - Radial Gradient errors favor near-zero CTE housing
    - All designs will require that gradients within the glass reflectors be kept small (~0.5C)
    - Axial, Diametrical gradients generally less stringent (~1C)



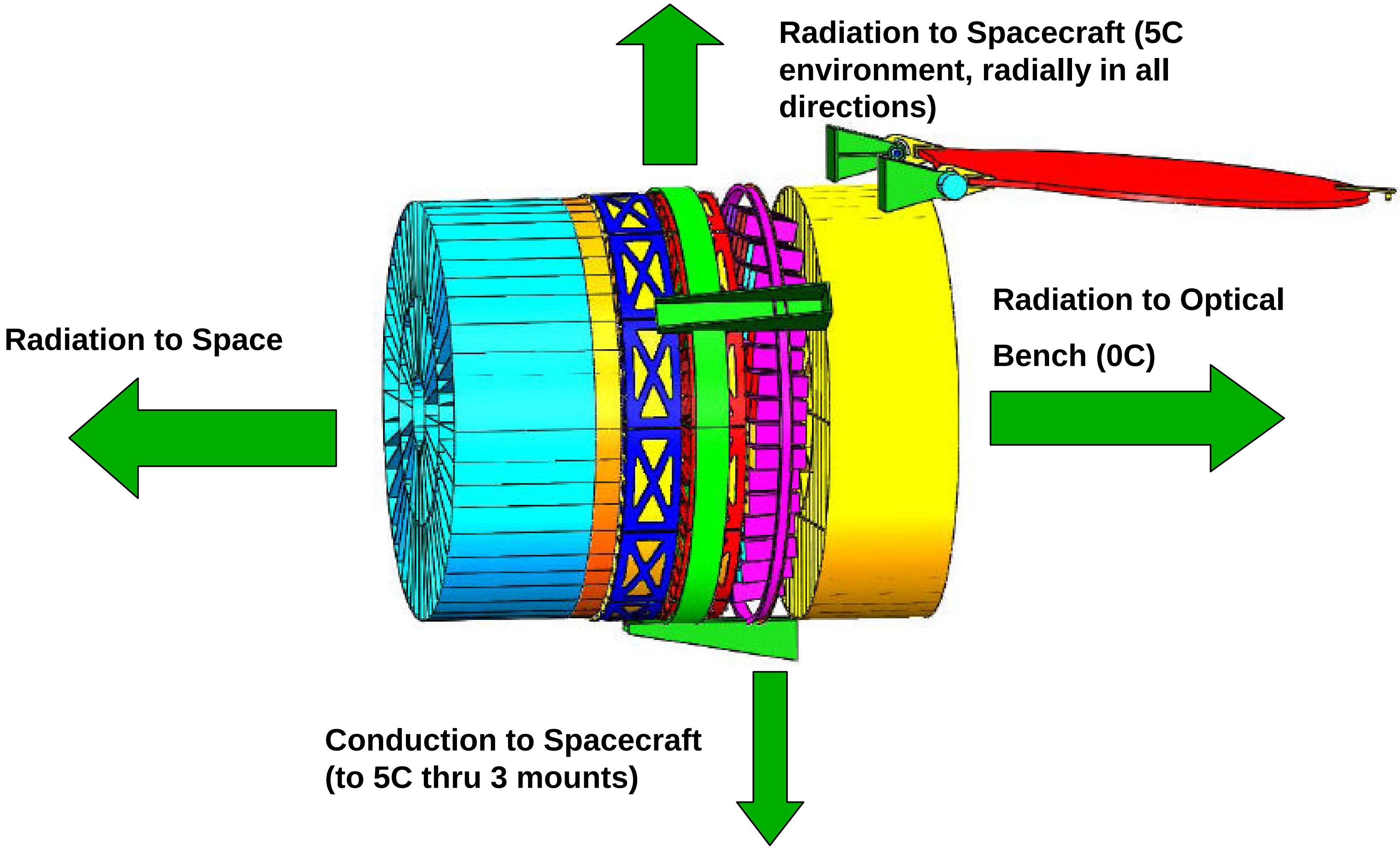
Sample Reflector Temperature Distribution

FMA Power Requirements Flowdown for Reference Concept

- FMA Power
  - Basic Requirement: Overall heater power should be less than 400 Watts
  - Four major heat losses estimated from the Reference Concept
    - Radiative loss thru forward aperture to space: 300W
    - Radiative loss thru aft aperture/gratings to Optical Bench: 70W
    - Conductive loss thru mounts to Spacecraft: 20W
    - Radiative loss from insulated surfaces (cylinder): 10W
  - Estimates based on Reference FMA Concept including a pre-collimator study
  - FMA Interface Temperature Requirements for Study:
    - Optical Bench Effective Temperature: 0C* to 10C
    - Spacecraft Temperature: 5C* to 15C

      *used for estimates above

FMA Interface Heat Flows for Study

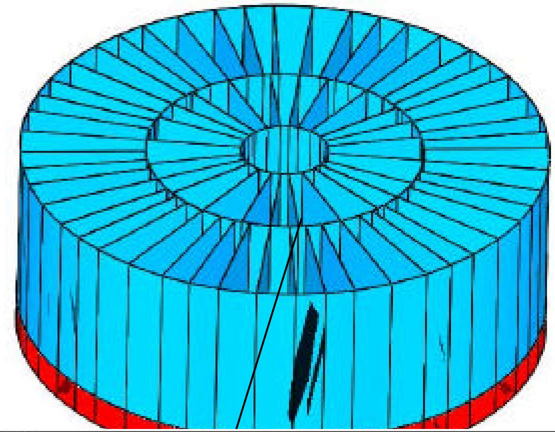


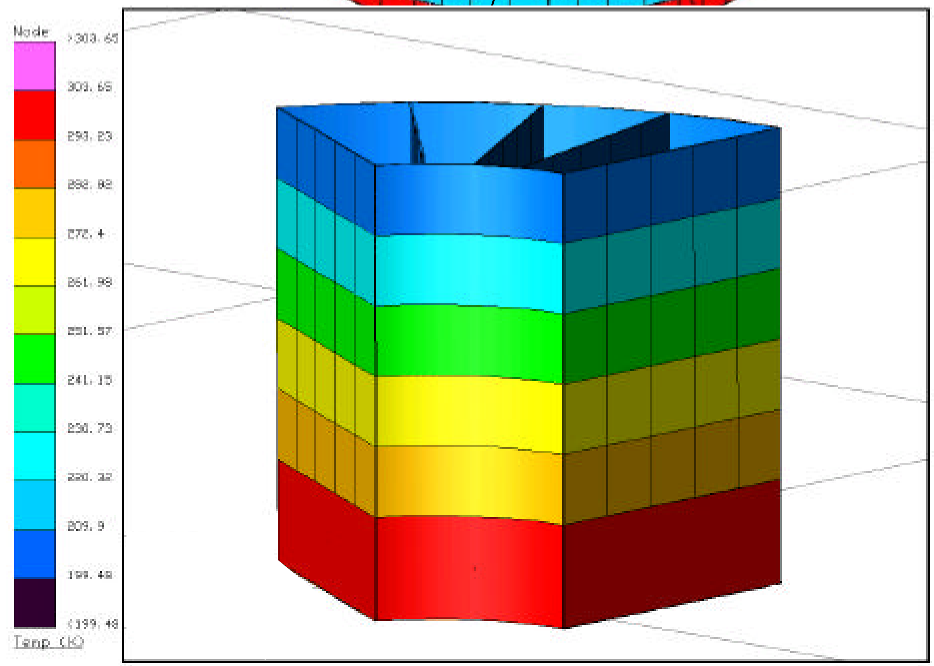
Thermal Control of Closely-spaced Wolter-I Optics

- Optics design creates thermal deep cavity behavior
  - Emittance of aperture ~1.0 for optics
    - 1.6 m optic would radiate ~850W without any aperture protection
  - Most of the power radiated from forward ends of the reflectors
- Thin glass reflectors have very low in-plane conductance to distribute heat and mitigate gradients
  - Gradients for open aperture exceed 40C
  - Curved reflector with finite CTE and temperature gradient creates distorted shape, even without housing-induced errors
- Direct application of heaters to glass not practical
- Needed: Benign thermal environment for optics
  - Standard approach: Thermal Pre-collimator
  - Aluminized film over aperture severely attenuates low energy x-rays
  - Other?

Thermal Pre-collimator for Reference Concept (Design Features)

- Two related functions for all pre-collimator designs:
  - Control glass reflector gradients
  - Reduce power radiated to space
- Thin mirrors cannot be heated directly – control provided by radiative enviroment
- Radiated power is reduced by lowering effective aperture temperature
- Most designs create “tubes” that limit view of optics directly to spa

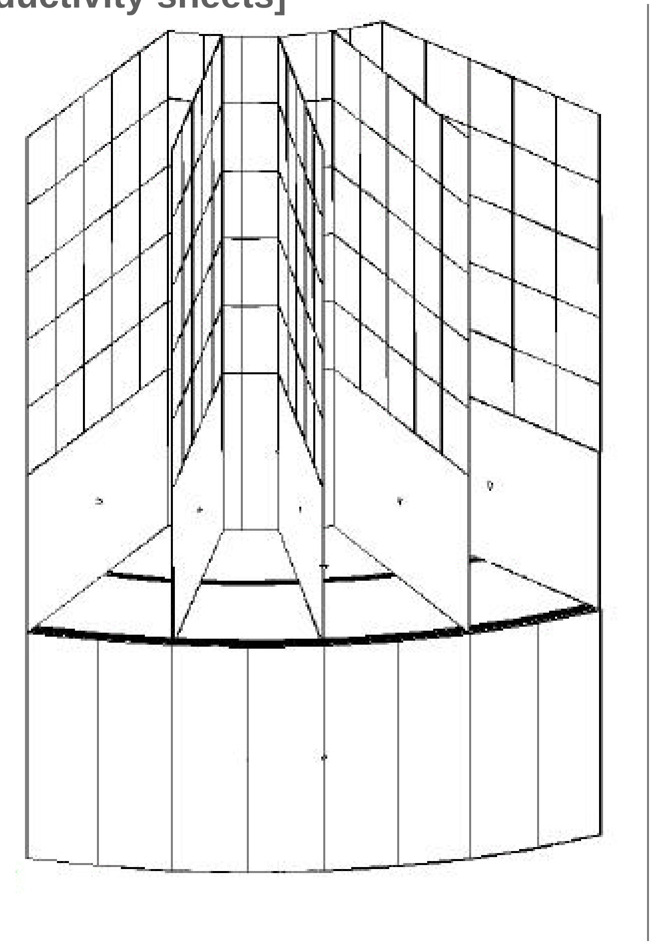




Pre-collimator Design Model

Pre-collimator Model for Reference Design

- Modeled groups of reflectors at two radial locations – midway and near outer boundary of module
  - Mirror distribution results differed, largely due to spacing difference
- Radial Vane design one of many options studied
- Design proved effective in controlling gradients in the reflectors while reducing radiated power (~1/3 open aperture loss)
- Vanes located over radial struts of SXT assembly to minimize obscuration



Design Areas for Contractor Study

- The radial vane design is tailored to the Reference Concept
  - Designed to lay within optical areas already obscured by mechanical structure to limit additional obscuration
  - Radial form also minimizes alignment requirements
  - If mechanical design is different, another form may make more sense
- Reference Concept post-collimator has not been analyzed
  - Performance numbers based on pre-collimator "efficiency"
  - Vignetting issues related to both straight-through and grating dispersion are significant
  - Grating thermal requirements are similar to the mirror module's
- Contractor study designs should consider:
  - Gradient control, esp. in individual reflectors, and housing/reflector interactions
  - Power requirements for FMA, esp. if significantly different from estimates presented for the reference design
  - Any special advantages or disadvantages of the mechanical design, construction, or mounting and alignment

Reference Materials for the Thermal Study

- “Thermal Analysis of a Radial Vane Pre-collimator”; Freeman, M., Constellation-X Memorandum, 25 July 2003
- “Thermal Control Study of the Constellation-X Telescope Aperture”; Boyd, D. and Freeman, M., Proceedings of the 32nd International Conference on Environmental Systems, San Antonio, TX, 15-18 July 2002 (Paper 2002_01_2372)
- “Pre-collimators: Passive On-orbit Thermal Control for Space-based Telescope Apertures”; Lynch, N., Boyd, D., Freeman, M., Proceedings of the Sixth European Symposium on Space Environmental Control Systems, Noordwijk, The Netherlands, 20-22 May 1997

Summary

- All temperature requirements for the FMA are derived requirements based on the Angular Resolution Error Budget
  - Derived requirements have to be based on the particular design and are presented here only for reference purposes
  - Gradients within reflectors and reflector/housing interactions are key in the Reference Concept
- Power requirement is based on estimates made using the Reference Concept and pre-collimator model
- Radial vane pre-collimator demonstrates viable concept with closely-packed x-ray optics
- Design of thermal hardware should consider secondary requirements like vignetting and assembly issues

Constellation X

The Constellation X-ray Mission

X-Ray Test and Calibration

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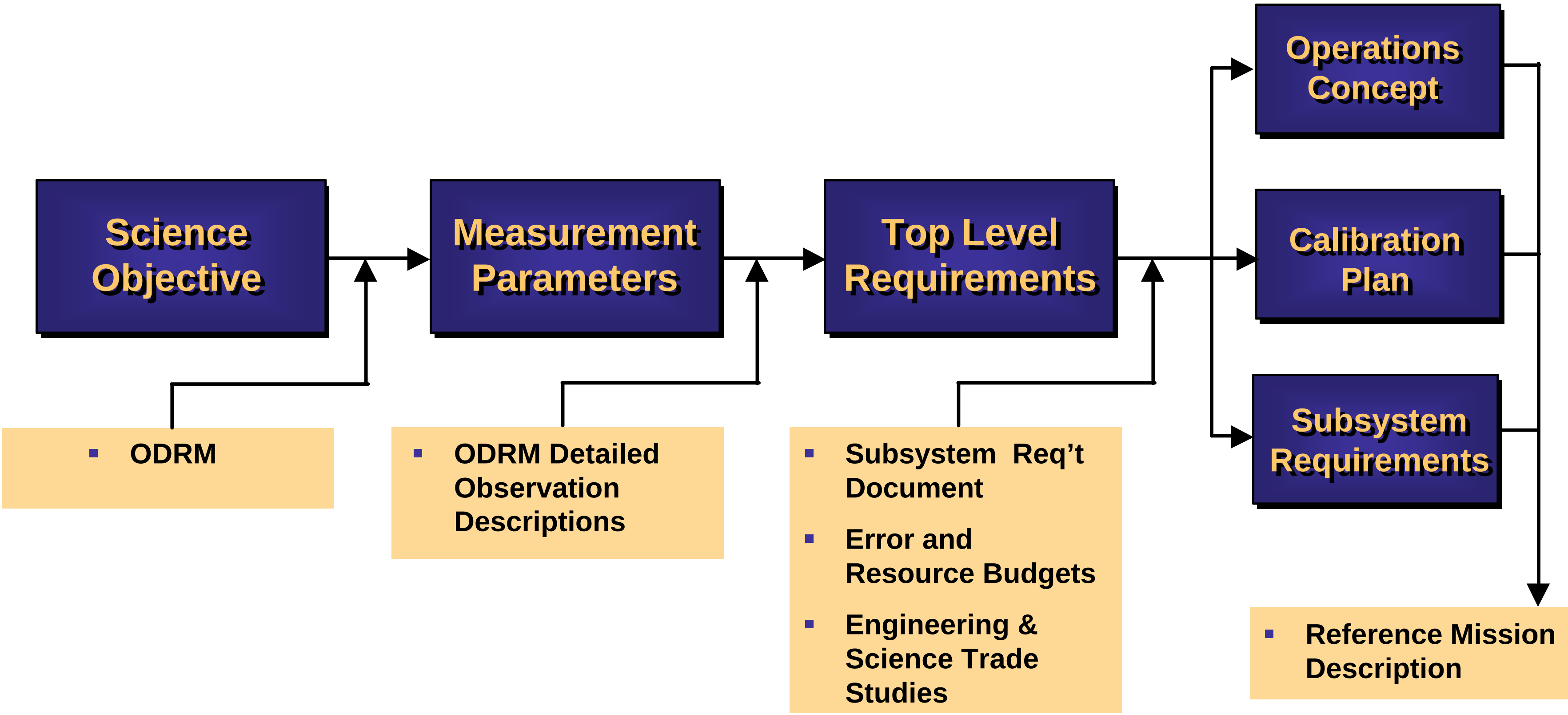
Outline

- Requirements Traceability
- Mission Performance Requirements
- FMA Requirements flowed from the Mission
- Verification and Calibration Philosophy
- Calibration Trades
- Calibration Facilities
- What are we expecting from you?

Requirements Traceability

- Process traces science objectives to measurement requirements to system and subsystem requirements



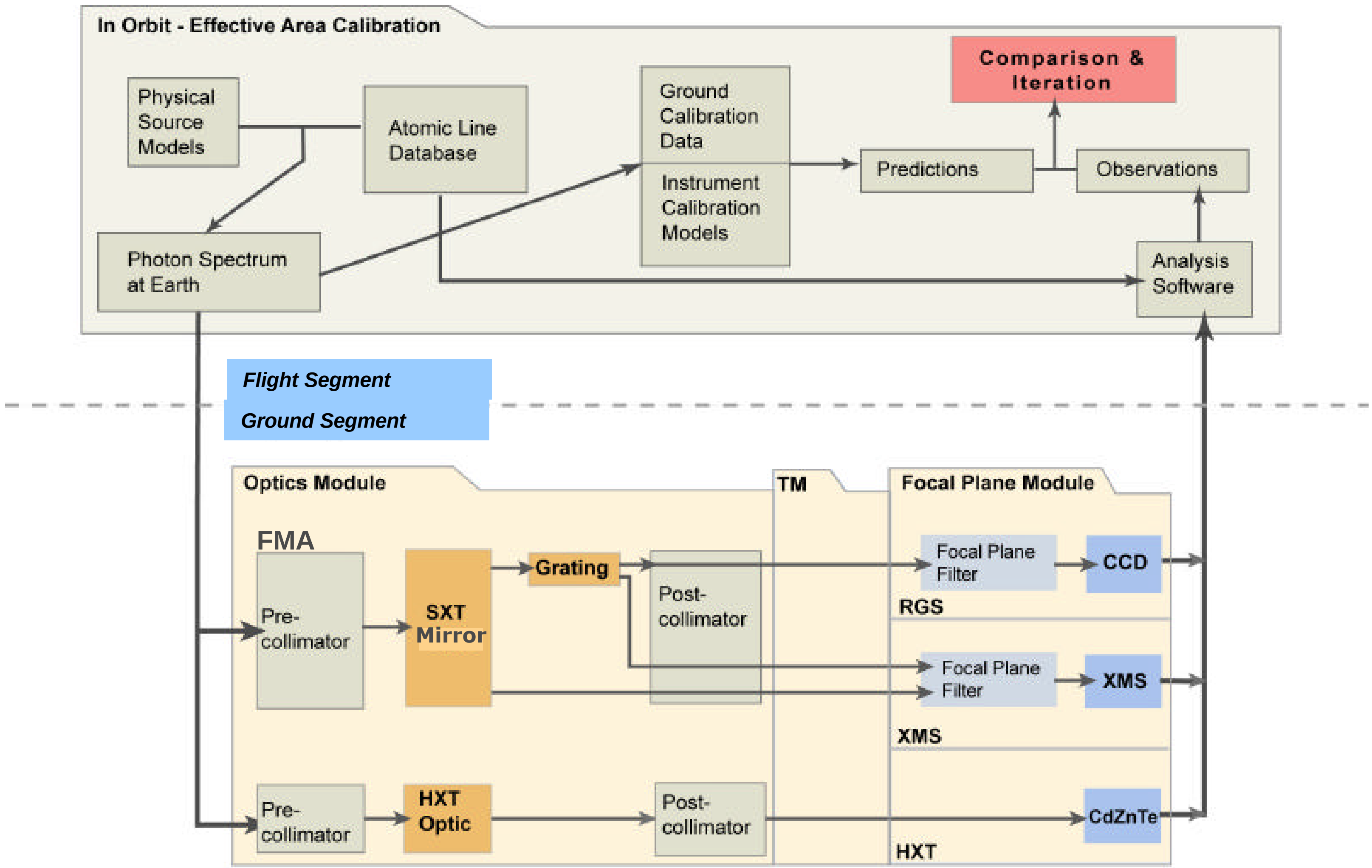
Systems Approach to the Mission

- Mission top level requirements are flowed to FMA, instruments and subsystems via error budgets and performance simulations
- Comprehensive systems approach: flight segment, ground segment, operations and calibrations are considered together.
  - Flow down of requirements is carried into calibration requirements via the Calibration Plan
  - Flow down of requirements for Mission Operations as well as the flight elements via the Operations Concept Document

FMA Requirements

- FMA performance to be verified or calibrated
  - Effective Area
  - FOV
  - Angular Resolution
- FMA Implementation Requirement
  - Design approach must lend itself to ground verification and calibration at subsystem and system levels

Block Diagram for Effective Area Calibration



FMA Verification and Calibration ⇒ Design Impacts

- Designs must reflect the verification/calibration issues & requirements
  - A number of assembly approaches (various combinations of mirror module and submodule concepts) appear to share a common verification and calibration flow
  - An approach that *requires* assembly of a complete FMA prior to *any* verification and calibration is probably not viable
  - Verification and calibration of the gratings with the mirror depends on the GIS implementation
  - Calibration of the gratings with the mirror must take into consideration finite source distances and a non-flight-like configuration
  - All verification and calibration activities need to account for facility capabilities and limitations
- ALSO: in moving from 12.5 arcsec (requirement) to 4 arcsec (goal), significant portions of the calibration/verification flow may change, including the dominant terms – will require development of detailed error budgets

Calibration Philosophy

- Mission calibration philosophy addressed in Draft Constellation-X Calibration Plan (12/11/02)
- Requirements source is the Constellation-X Top Level Requirements Document
- Philosophy is to calibrate on-orbit to the largest extent possible
  - All parameters calibrated on-orbit are verified during ground testing!
  - FMA Ground Calibrations:
    - Optical axis
    - Effective area (may not be exhaustive)
    - Grating throughput, efficiency, resolving power, dispersion direction, etc.
  - FMA on-orbit Calibrations:
    - Final Point Spread Function (PSF) (on- and off-axis)
    - Ghost images & Stray light
    - Plate scale
  - Calibration accuracy requirements not yet fully defined. Preliminary mission level accuracy requirements are provided in the Constellation-X Top Level Requirements Document

FMA Verification Issues

- **Verification of the assembly/alignment process required on "first units"**
  - Will require further study to determine how many additional units need to be verified, and how extensively.
- **How much testing early on to gain confidence?**
  - primary/secondary alignment, mirror figure, effective area?
  - Module-to-module or module to FMA?
  - Module/Pre- and Post-collimators/RGA as a unit?
  - RGA (or some subassembly) to FMA (or module)?

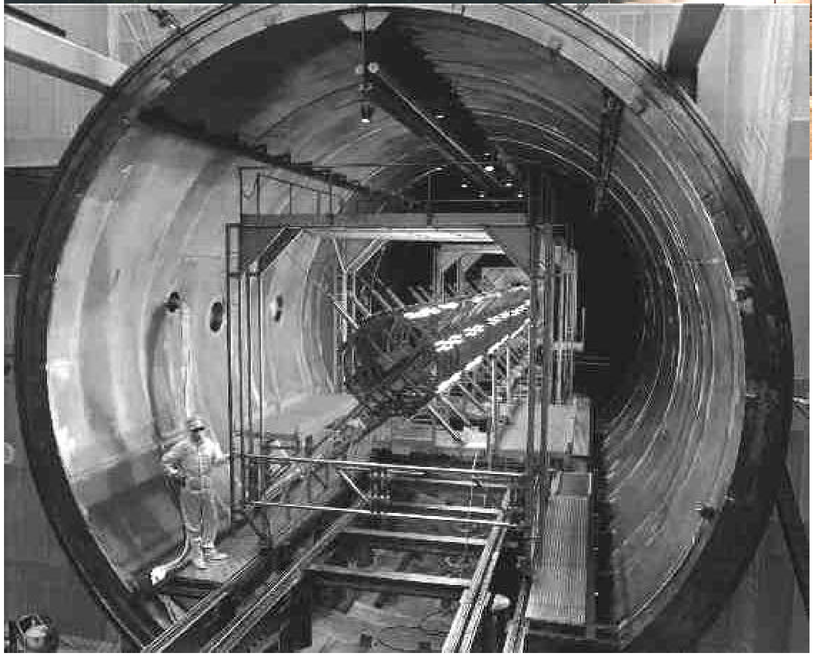
Calibration Phases

- As defined in the Draft Constellation-X Calibration Plan
- Phase 1: Pre-delivery calibrations of individual detectors and optics
  - FMA – Primarily the responsibility of the FMA contractor
  - Calorimeter
  - HXT
- Phase 2: System Level calibrations — Supported by the FMA contractor
  - Phase 2a: Optics Module (OM)
  - Phase 2b: Focal Plane Module (FPM) calibrations
  - Phase 2c: Telescope Module (OB)
  - Phase 2d: End-to-End calibrations (TBD)
- Phase 3: On-orbit calibration activities:
  - Phase 3a: Early Operations Verification Activities and Calibrations
  - Phase 3b: Normal Operations Calibrations

Major Calibration Trades

- **Possibility of detailed ground calibration of subset with subsequent cross calibration on-orbit of remaining telescopes**
  - Calibrate 1 telescope/observatory/FMA
  - Calibrate 2 telescopes - 1 per launch vehicle
  - Calibrate 4 (full cal)
  - Use a single mirror module as a transfer standard
- **When to calibrate: at FMA level or at telescope level?**
  - At FMA level
  - Pre- or Post-RGA installation?
  - At telescope level?
- **Where to calibrate?**
  - One site versus multiple sites (issues of cross calibration and possibly, ITAR)
  - Consider potential modifications to existing facilities (re increasing beam size at XRCF)
  - Consider both vertical and horizontal facilities
  - Consider facilities using EUV wavelengths for some calibrations

MSFC Optics Test Facilities – XRCF



- **X-Ray Calibration Facility**
  - 530-m long
  - Utilization
    - *Einstein* (HEAO-2) testing before facility renovation
    - *Chandra* (AXAF) calibration
    - NOAA SXI, Con-X, SAO's XRT
    - JWST cryo-optical testing
- **Chamber:**
  - 22.9m long
  - 7.3m diameter
  - Capable of focal lengths up to 13m with current detector setup
  - Full illumination of apertures up to 1.45m (limited by guide tube and primary gate valve)
    - Sub-aperture testing allows up to 120deg on FMA

MSFC Optics Test Facilities – Stray Light Facility

- **Stray-Light Facility**
  - 100-m long
  - Utilization
    - Originally stray-light testing
    - X-ray interferometry, etc.
    - Hard x-ray (e.g., HERO)
    - Technology development for FMA and HXT
  - Suitable for FMA modules, but not complete FMA

Summary

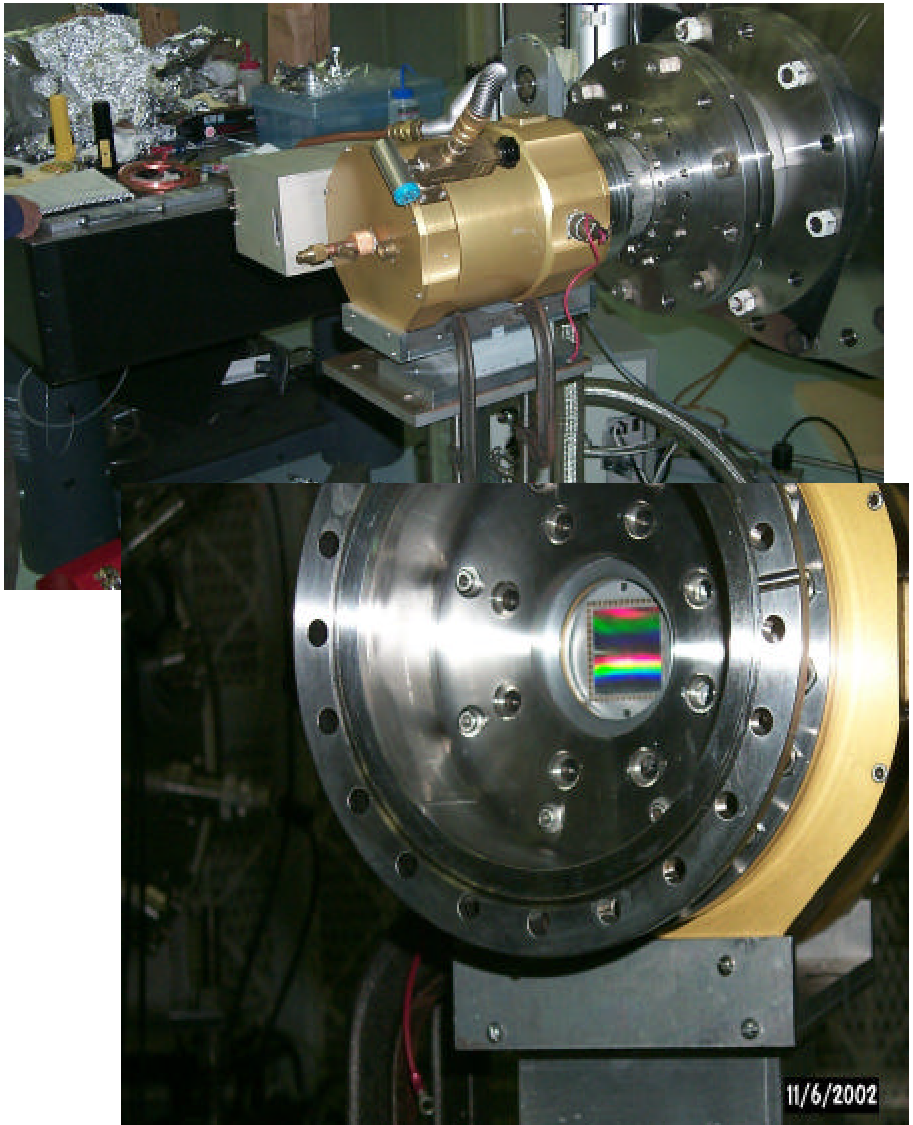
- The Constellation-X calibration philosophy has been developed
- Preliminary list of trade studies related to calibration and verification have been identified
- Ensure the FMA Study design is consistent with the mission plan for early testing, ground verification and calibration

Backup Slides

XRCF Sources and Detectors

- **Currently available x-ray sources:**
  - a fixed-anode (electron-impact) source, with interchangeable targets and selectable x-ray filters;
  - two rotating-anode sources, each behind a monochromator (one with selectable double crystals, the other with selectable erect-field reflection gratings); and
  - a Penning source, for producing low-energy lines.
- **Currently available detectors:**
  - Flow proportional counter (with selectable apertures)
  - Solid-state spectrometer (with selectable apertures)
  - A high-resolution microchannel-plate imager.
  - Multiple flow proportional counters and a solid-state spectrometer serve as beam-normalization detectors.
  - Scanning detectors for beam uniformity

X-ray CCD Detector



- **Advantages for testing**
  - Large field of view
    - 37-mm (1.5-in) square
      - 13 arcmin @ 10 m
    - 2048 ´ 2048 pixels
  - Very good spatial resolution
    - 18-mm square pixels
      - 0.4 arcsec @ 10 m
- **Disadvantages for testing**
  - Front-illuminated device
    - Little response < 0.8 keV
  - Slow read-out electronics
    - 100-s read-out
      - Bad for photon counting
- **BUT a new, BI device may be available later this year.**

Constellation X

The Constellation X-ray Mission

Acronyms/Glossary

Acronyms

- AO – Announcement of Opportunity
- C-X – Constellation X
- CCD – Charged Coupled Device
- CDA – Centroid Detector Assembly
- CSD – Contract Start Date
- CTE – Coefficient of Thermal Expansion
- FMA – Flight Mirror Assembly
- GIS – Grating Integrating Structure
- GSFC – Goddard Space Flight Center
- H – Hyperbolic reflectors (ref design)
- HXT – Hard X-ray Telescope
- HPD – Half Power Diameter
- I&T – Integration and Test
- keV - Kilo electron Volts
- LTP – Long Trace Profilometer
- OAP – Optical Pathfinder Assembly
- OM – Optical Module
- P – Primary/ Parabolic (ref design) reflectors
- PARAT – Production Alignment Robotic Assembly Tool
- PDR – Preliminary Design Review
- RFC – RGS Focal plane Camera
- RFI – Request for Information
- RGA – RGS Grating Array
- RGS – Reflection Grating Spectrometer
- ROM – Rough Order of Magnitude
- RoSAT – Rontgen Satellite
- RSS – Root Sum Square
- S – Secondary Reflectors
- SAO – Smithsonian Astrophysical Observatory
- SRC – Spectroscopy Readout Camera
- SXT – Spectroscopy Xray Telescope
- SOW – Statement of Work
- TRIP – Technology Readiness and Implementation Plan
- TRL – Technology Readiness Level
- XMM – X-ray Multimirror Mission
- XMS – X-ray Microcalorimeter Spectrometer
- ZOC – Zero Order Camera

Glossary

A

Angular Resolution
The angular resolution is the ability to spatially resolve two point sources next to each other.

C

Contractor's Study Design
The FMA design that each contractor develops as part of the effort on the FMA systems study contract.

Collimator
A thermal control device to provide thermal isolation between a source of heat and a heat sink. It may be active, passive or a combination depending upon specific usage. The FMA uses both a pre and post collimator.

-Precollimator – Used to provide thermal isolation between the front of the FMA and cold space at L2.

-Postcollimator – Used to provide thermal isolation between the exit of the FMA and the Optical Bench/Focal Plane.

Cover, Internal
Mechanical cover over the post collimator exit to protect the FMA from damage and contamination during assembly, integration, transportation, launch and transit. The internal cover is designed to be deployed only once on orbit.

F

FMA
Flight Mirror Assembly. This assembly consists of the Pre and Post Collimators, the Mirror (consisting of all Primary and Secondary reflectors and their supporting structure),the RGS grating array and the grating integrating structure.

FMA Reference Concept
The configuration of the FMA documented in the "FMA Reference Package". This is the result of conceptual design performed prior to this study by the Constellation-X Project. This is one of the many possible configurations for FMA.

G

Grating Module
An assembly of gratings into a mechanical housing of approximate size 11cm X 11 cm X 22 cm.

Grating Integrating Structure
Mechanical mounting structure for holding and aligning the Grating Modules in the FMA. This structure supports the grating modules between the flight mirror and the post-collimator within the FMA and may be separable, monolithic structure(s), or integral to the FMA structure.

M

Mandrel, Forming
Mandrel used to provide overall shape to flat glass sheets through a heating and slumping process. The resulting formed glass substrates are used to make reflectors.

Mandrel, Replication
Mandrels that are used to replicate the final reflector figure and finish onto the glass substrates using an epoxy replication process and gold coating on the mandrel.

Mirror
See XST Mirror

Mirror Module
An assembly comprising of a Primary(P) Mirror Sub-module and a Secondary(S) Mirror Sub-module.

Mirror Sub-module (P or S)
An assembly, containing multiple reflectors, properly aligned. P stands for primary or the first reflector layer in the optical path that X-rays pass, and S stands for secondary or the second reflector layer. In the case of Wolter I Optics. P reflectors are a Parabola and S reflectors are a Hyperbola consistent with the definition.

P

P and S
See Primary and Secondary below.

Primary(P) and Secondary(S)
Primary Reflector is the first reflector from which X-rays are reflected. Secondary reflector is the second reflector from which X-rays are next reflected. In Wolter I optics the first reflector surface is formed by revolving a Parabola on the optical axis and the second is formed by revolving a Hyperbola.

R

Reference Concept
See FMA Reference Concept

Reflector
Reflector is basic unit of optics providing a surface for grazing incidence X-ray reflection

RFC
RGS Focal Plane Camera

RGA
RGS Grating Array is comprised of all the gratings modules and supporting structure (GIS). When in place in the SXT FMA the RGA reflects and disperses a portion of the incoming X-rays onto the RFC. Some X-rays pass through the RGA to the FMA focus without deflection..

Ring Structure Assembly
Mechanical structure in the FMA Reference Concept to which all Mirror modules are mounted. Could also provide attach points for the Pre and post collimators and the grating integration structure. The ring structure assembly also mounts the FMA to the optical module.

S

Shells
A shell is a complete surface of revolution for reflection of X-rays. Shells in the FMA Reference Concept optical design are numbered from 1 through 230 starting at the outer most radius of the mirror inward.

Study Design
See Contractor's Study Design

Sub-module
See Mirror Sub-module

SXT
Spectroscopy X-ray Telescope. The SXT comprises the FMA, the XMS, and the RFC to perform spectroscopy on the celestial X-ray sources in the energy range of 0.25 keV to 10 KeV.

SXT FMA Flight Mirror Assembly
This is the optical systems of SXT that focus and disperse X-rays. It also includes thermal and structural subsystems, and the aperture door that aid in performing the functions on ground and the space.

SXT Mirror
This is the assembly of all mirror modules in the FMA. This does not include thermal subsystem and grating assembly.

XMS
X-Ray Microcalorimeter Spectrometer